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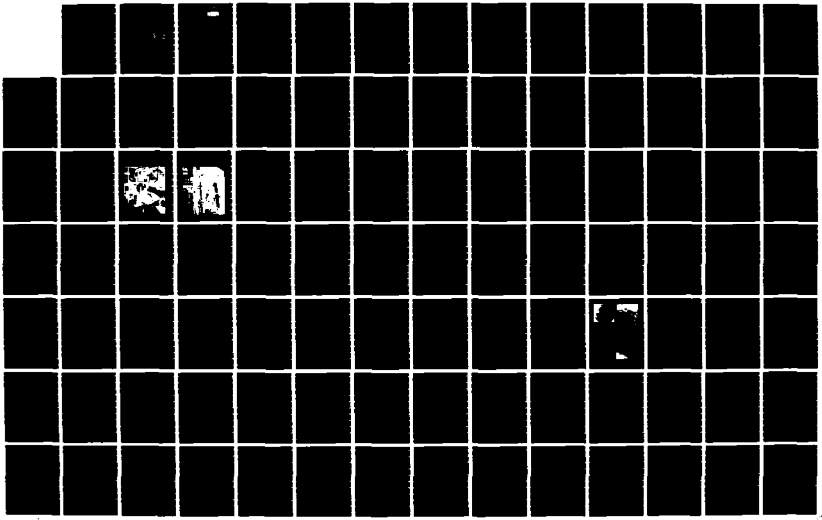

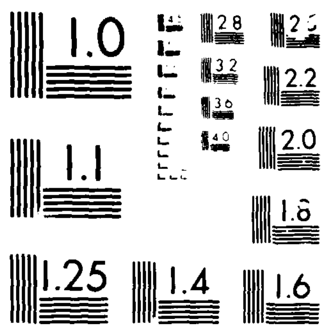
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"RELIABLE WELDING OF HSLA STEELS BY SQUARE WAVE PULSING USING AN ADVANCED SENSING (EDAP) TECHNIQUE"

Preliminary research for the real time control of nugget size and penetration, by sensing and controlling fundamental oscillations of the weld puddle, using the GTAW process.

Detailed results of MILLI-PULSE, MICRO-PULSE and POLY-PULSE welding of A710 steels, with some new observations.

C. Connelly, G. J. Fetzer, R. G. Gann, T. E. Aurand

APPLIED FUSION TECHNOLOGIES, INC.
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30 April 1986

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"RELIABLE WELDING OF HSLA STEELS BY SQUARE WAVE PULSING USING AN ADVANCED SENSING (EDAP) TECHNIQUE"

This Final Report has been reviewed and is approved.

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Preliminary research for the real time control of nugget size and penetration, by sensing and controlling fundamental oscillations of the weld puddle, using the GTAW process.

Detailed results of MILLI-PULSE, MICRO-PULSE and POLY-PULSE welding of A710 steels, with some new observations.

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SUMMARY

"RELIABLE WELDING OF HSLA STEELS BY SQUARE WAVE PULSING USING AN ADVANCED SENSING (EDAP) TECHNIQUE"

Preliminary research for the real time control of nugget size and penetration, by sensing and controlling fundamental oscillations of the weld puddle, using the GTAW process.

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A four part program was undertaken for the purposes of improving the reliability and predictability of welding. This was a Phase I SBIR research effort, funded by ONR, to demonstrate feasability of these proposed concepts:

1. Control automatically, in real time, weld nugget size and penetration.
2. Explore the use of square wave pulse welding for HSLA steels.
3. Develop a data base for pulsed GTA welding of A710 steel.
4. Determine the value of using an advanced video system for welding research

Most of this work was to proceed concurrently and simultaneously. However, difficulties encountered when making single pass, full penetration welds on A710 steels led to the completing of some of the research separately. The major concepts of weld control and pulse welding were both completed with very successful results.

Several important discoveries were made:

A. **Large weld puddles may exhibit several oscillation frequencies. Some of these secondary oscillations can readily be controlled, such as, by superimposing a high frequency MICRO-PULSE current on the BASE current. These secondary oscillations may help to contribute to a final control scheme.**

B. **A Traveling Wave (or standing wave) may interfere with accurately sensing weld puddle oscillations. This wave can be controlled or eliminated by controlling the amplitude of the puddle excitation pulse.**

C. **The technique of using a sharp diminishing current pulse, may be more reliable than a superimposed high current pulse for developing fundamental puddle oscillations.**

D. **POLY-PULSE welding, superimposing MILLI-PULSE (1-999 Hz) on MICRO-PULSE (1 K Hz - 50 Hz), produced some unusual results in welding A710 steel. A "Transition" type of weld bead was identified. The "Transition" type weld puddle is unstable producing uneven nugget shapes.**

HSLA steels are important to the future of the construction industries, particularly marine fabrication. A710 steel is a logical alloy for initially developing a data base for welding these steels. Plates 3/8" thick using a tight square butt joint was the starting basis for this research. However, single pass full penetration welds could not be produced consistently. All welds completed with this thickness of plate were very large. These oversized welds made at high current levels have the disadvantages caused by overheating, including grain growth and distortion. Therefore, the pulsed GTAW process should be limited to the 1/4" thick joints where full penetration is required.

Very important to this research was the development of the Extended Range Video (ERV) system as a research tool for welding. This high resolution system included image enhancement, high speed picture rates, and both timing and measuring indexes. Most valuable was the capability of superimposing on the video screen (CRT) two camera images in a split screen fashion. This provided the capability of comparing waveforms generated by the weld puddle oscillations to the actual puddle and arc. All final welds with waveforms and puddle images are recorded on video tape for further study.

As compared to steady D.C. welding, pulse welding in both the MILLI-PULSE and MICRO-PULSE ranges all resulted in metallurgical improvements, including grain refinement, removal of porosity and breaking up of structures in the nugget. Additionally, a considerable increase in depth of penetration can be expected by using either of these pulse methods.

POLY-PULSE welding also exhibited the same metallurgical advantages. However, penetration and weld bead size could either be wide and shallow, or deep and narrow, according to the combination of pulse rates selected. The welding engineer has an excellent new tool for controlling bead shape. He can now select a full penetrating weld or wide cap pass by changing pulse rates only.

Using **EDAP** (Electro Dynamic Arc and Puddle Control) for control of weld nugget size and depth of penetration appears to be a distinct possibility. This can be accomplished without having back bead access or expensive and bulky sensors placed in the hostile environment of the welding arc. The fundamental oscillations of the weld puddles, induced by a sharp change in current, provides the information that directly relates to puddle size. These Natural Frequencies (f_N) sensed thru the arc have very close correlation to nugget size and back bead width. Welds made using a laboratory research **EDAP** system, employing both computer and video analysis, confirms this relationship.

Research was done on two levels. Level I research was used to prove the **EDAP** concept and develop the video system. Level II **EDAP** research entailed using a more sophisticated system of frequency estimation, involving a scientific computer. This final system was operated in an observation mode only. A welder control system was designed and built. Then a basic welding scenario was used for computer simulation during final testing of the control. This welder control system has not been put in place and, therefore, has not been tested under actual welding conditions, due to time constraints.

The feasability of using fundamental oscillations of the puddle for nugget size and penetration control has been clearly demonstrated. The welding operator finds this frequency information out of his realm of observable parameters, so therefore, an electronic system of control such as **EDAP** becomes necessary.

Improving the reliability and predictability of welding can be further accomplished using an advanced control system such as **EDAP**. Further improvement and control is offered with welds made by square wave pulsing of the arc. It is believed that both the military and commercial establishments will benefit by continued development and application of these methods.

PREFACE

This Phase I research work was contracted with the OFFICE OF NAVAL RESEARCH, Department of the Navy, through the SBA-SBIR program. The primary purpose was to demonstrate feasability of a welding control system and provide the results of pulse welding HSLA steels. This is a final report with recommendations, **which include four areas of preliminary research combined into one report.** This accounts for overall size of the report. This research went beyond just demonstrating feasability. The investigators in this work wanted the most assurance possible that a Phase II program would result in the successful development of valid commercial products.

Applied Fusion Technologies, Inc. and the authors would like to thank all who participated in this work as subcontractors, suppliers or consultants. This work would not have been possible without the original discovery by Dr. Damon Kotecki and the continuing work at Ohio State by Mr. Renwick and Dr. Richardson, and the work at Massachusetts Institute of Technology by Ms. Zacksenhouse and Dr. Hardt.

The professional metallographic examinations completed by Mr. Jay Dwight, of Dwight Testing Laboratories in Chehalis, WA, was a major contribution to the interpretation of the results, and he also was of considerable help during the ongoing research.

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1.0 INTRODUCTION

The primary objective of this Phase I work was to demonstrate the **feasability** of developing a method for improving the **reliability** and **predictability** of welding, and the benefits of using the pulsed GTAW process.

Phase I Research was conducted at two levels:

A. **LEVEL I**, determined the reliability of the **EDAP** concept for full penetration welds on relatively thick steels. Most of this level was devoted to **EDAP**; however, the basics of welding of A710 steel was also researched. The implementation of the video system was developed during this preliminary level.

B. **LEVEL II** incorporated more sophisticated test equipment with the primary objective of determining the feasability of developing the **EDAP** control system. Pulse welding research and the development of a data base for A710 steels was also a part of this level.

1.1 CONTROL RESEARCH EDAP

Most of the emphasis of this Phase I preliminary research was devoted to the concept of **EDAP** (Electro Dynamic Arc and Puddle Control) for the GTAW process. The method studied in great detail was to use the Natural Frequencies (f_N) of the molten weld puddle to provide both nugget size and penetration information.

The main purpose was to provide a method for developing information that could control critical root bead penetration in heavier plates, particularly where back side access is not available. Also, the system would not require bulky sensors located in the hostile environment of the arc. Finally, the system will provide **real time control** of both nugget size and penetration.

The successful testing and implementation of both hardware and software is a major part of this research.

1.2 PULSE WELDING

The many advantages of pulse GTA welding have been known for years. Documentation of the advantages of this process has been limited with almost none for HSLA steels. This part of the research work confirmed capabilities of producing refined grain structures and reducing porosity.

Penetration control has been accepted as a major benefit to pulse welding. This research, however, has demonstrated that **there is not a straight line relationship between pulse rates and penetration.** Reduced heat input was confirmed,

demonstrating that equal penetration can be obtained at substantially lower current levels.

Initial research was conducted both at MILLI-PULSE (1-1000 Hz) and MICRO-PULSE (1 K Hz - 50K Hz) levels. Final research was conducted using the POLY-PULSE capabilities of the ARCON welding power supply, wherein MICRO-PULSE is superimposed on MILLI-PULSE.

1.3 DATA BASE A710 STEEL

The original concept was to develop a data base for the pulsed GTA process simultaneously with **EDAP** development and pulsed welding research. The difficulties in single pass welding 3/8" thick sections of A710 steel limited the results of this portion of the research. The difficulties themselves provide information which should be of value to the welding engineer.

A major discovery in this work was the identification of a "TRANSITION" type weld puddle. It is believed this type weld puddle exhibited mixed convective type flows.

This research was conducted using weldments cut from a single plate of the same chemical analysis. Therefore, reliable extrapolation of this data and application to other HSLA steels or thicknesses needs to be confirmed.

1.4 EXTENDED RANGE VIDEO (ERV)

The use of video as a welding research tool has been limited until the last few years. Full development of the process as it is applied to viewing the welding puddle is being actively pursued by various companies. Extending the concept still further, a research system was put together offering the following main features:

A. Enhanced high resolution recording and viewing.
B. High speed recording with multiplex viewing.
C. Split screen capabilities.

The major need was to provide a research tool that would reduce the requirement of remaking similar welds, by being able to review previously made welds at any time desired.

2.0 EDAP (ELECTRO DYNAMIC ARC AND PUDDLE CONTROL)

2.1 EDAP BACKGROUND

In the last several years there has been a significant amount of research aimed at automating the control of weld size (Ref. 1, 2, 3). Techniques have ranged from ultrasonic reflection measurements to large scale vision based systems including infra-red sensing. Another technique which has attracted some attention is that of using oscillations of the weld puddle to monitor the weld size. The chronological works by others for weld puddle dynamics are as follows:

2.1.1 Kotecki.

Weld puddle oscillations were discovered in the early work by Kotecki et al (Ref. 4), who at that time were interested in the mechanisms involved in the formation of ripples during the solidification of the weld puddle. Kotecki found, through the use of high speed cinematography, that the formation of ripples in the weld was due to periodic fluctuation of the arc, due to the presence of an AC component in the arc current. He notes that when using a pure DC arc source (i.e., batteries) ripples are not formed. Kotecki also shows that there are two modes of oscillation of the weld puddle. He observed a natural frequency of the weld puddle just prior to solidification of the weld, RANGED BETWEEN 45.0 and 70.0 CPS (GTA spot welding on iron plates in a very clean environment).

2.1.2 Renwick and Richardson.

In a similar work Renwick and Richardson (Ref. 5), have shown a correlation between the Natural Frequency (f_N) of the weld puddle and the size of the puddle. In Renwick's work the arc voltage is monitored on an oscilloscope while pulsing the arc current. The Natural Frequency (f_N) is identified using the oscilloscope trace. High Speed Cinematography was also used in this experiment to verify that the weld puddle was oscillating at the same frequency as the arc voltage. Renwick limited his work primarily to stationery arcs with partial penetration. As such the work has little practical application other than to invite further experimentation under more realistic conditions. The Natural Frequencies (f_N) observed by Renwick and Hardt RANGED BETWEEN 100 and 300 CPS.

2.1.3 Zacksenhouse and Hardt.

A more complete work was published by Zacksenhouse and Hardt in which a theoretical model of the puddle is offered (Ref. 6). Based on this model, the impedance of

the weld puddle is derived. In Zacksenhouse's first experiment a sinusoidal current is super-imposed on the welding arc current. Later a laser was used to monitor the fluctuations of the bottom side of the weld puddle. As the frequency of the AC current component is varied, the output of a photodiode detector was monitored. Peaks in the photodiode output as a function of the scanned frequency thus correspond to the natural frequency of the weld puddle. Unfortunately, this requires back side weld access.

An additional experiment was run by Zacksenhouse in which a broad band current source was superimposed on the arc current. The arc voltage was then fed into a spectrum analyzer and the puddle transfer function measured. In both experiments resonance frequencies RANGING BETWEEN 14 to 20 CPS were identified. These results agree fairly well with the results predicted by the theoretical model.

In addition, a control strategy was developed and simulated by Zacksenhouse, but was not tested in practice. Full penetration welds were used in this experiment but the signal capture techniques are either impractical, as in the case of the laser shadow method, or too bulky and somewhat unreliable, as in the case of the broad band spectral analysis technique. This introduces some difficult spectral estimation problems which would require complex mathematics to be implemented in real time.

2.1.4 Renwick and Richardson.

In a continuation of their early work, Renwick and Richardson completed experiments and extended their technique to traveling partial penetration welds with encouraging results (Ref. 7). They developed a proportional integral controller to maintain the size of the weld automtically, based on an estimate of the natural frequency of the weld puddle. Their experimental set up was "computerized," allowing for signal acquisition and providing automatic control of the weld background current.

The technique used was that of estimating the oscillation frequency of the weld puddle by counting the number of maxima and minima, in a set of arc voltages obtained immediately after a current pulse. This technique is essentially one of peak detection and is particularly unreliable in noisy environments. As such, they had to place error traps in their frequency estimation algorithm to compensate for the cases when the frequency estimate falls out of the range of reason. This is not inherently a negative characteristic of the algorithm

and indeed may be necessary in any algorithm. However, the simplistic technique of peak detection is not robust and is easily corrupted. It does have the advantage of being simple to implement and is computationally "fast."

Experiments were conducted to determine the effects of varying several different weld parameters including average arc voltage, shield gas flow, and weld travel speed, along with electrode shape.

The results obtained by Renwick and Richardson indicate that by automatically varying the background current for controlling the frequency of oscillation of the molten weld puddle, the width of the bead could be restricted to a three percent deviation. For this experiment the weld was run over a differential heat sinking backplate. These results were in comparison to a normal thirty percent deviation, when operating without automatically changing current. In addition, they demonstrated automated control of weld size on various types of steel illustrating the versatility of this approach.

2.1.5 Madigan and Richardson.

Most recently Madigan and Richardson made a presentation at the AWS annual meeting in Atlanta, Georgia. This continued their previous work with emphasis on full penetration welds on thin plates. Some noticeable limitations of their efforts were the slow travel speeds and slow signal processing. However, this work continues to demonstrate the relationship of weld puddle size to the fundamental vibrations of the puddle, initiated by a current pulse (P_e^+). A graph of frequency rates indicated that the larger puddles oscillated at frequencies close to those originally demonstrated by Kotecki. It appears that the result of this work at OSU is close to our observations at FUTEC and therefore very encouraging.

Most important, to be of general use in commercial and military applications, this technique requires further testing including full penetration welds, involving some type of joint, particularly on thicker plates. It is therefore necessary to develop the hardware and associated software to continue these investigations. These were the primary objectives of the Phase I EDAP feasibility research contracted by FUTEC.

2.2 EDAP RESEARCH

2.2.1 LEVEL I PRELIMINARY WELDING RESEARCH **EDAP,** A710 STEEL

This first level of research was conducted with initial emphasis on the feasability of the **EDAP** concept. Knowledge was also gained at this level for the possible difficulties in GTA welding of A710 steels.

The primary objective in the initial **EDAP** research was to confirm the results of previous researchers and to further extend this work to much larger weld puddles for traveling arcs. This primary effort was undertaken with the objective for determining the sensitivities of the concept and limits of operation.

Welding research began with stationery arcs where currents were controlled so that no weld puddle was developed. The results showed that there were no small signal arc voltage variances when no puddle existed.

Testing continued starting with developing small puddles and progressed to very large puddles sustained by current levels up to 600 Amps. Puddles were excited into motion using a current pulse superimposed on BASE current. It was demonstrated that weld puddle oscillations decreased with increasing puddle sizes. **It appeared that a plateau may exist for readily observing frequency responses in very large weld puddles.**

Welds were then made where the weldment was moved relative to the arc. This was to determine if variations were observable in the more practical traveling weld. These tests included using various joint designs. This variable made the concept of puddle oscillation feedback not necessarily more complex but imposed limitations on maximum travel speed.

A710 steel was used for most of Level I tests until the difficulties welding this steel were established. Comparison tests were then made on mild steel. Additional details can be found in other sections of this report.

A. EQUIPMENT

The initial set up for test welding was constructed primarily for proving the research equipment and the **EDAP** concept.

1. WELDING POWER SUPPLY

A welding power supply producing very clean D.C. current is required in order to observe uncontaminated small signal responses from the arc. Additionally, a very accurate welding system is required for this type of research work, one that will consistently produce the selected pulse rates and current levels.

The Arcon POLY-PULSE square wave machine used is a transistorized, series regulator type that can pulse to 600 Amps. This provides the high current capabilities for welding heavy plates. It also has sufficient control of pulsing and current to test all of the variables for **EDAP** development.

Difficulties were initially encountered with the cleanliness of the wave form produced by the POLY-PULSE welding machine. What was previously thought of as a clean output was not clean enough for this research. The first attempt to correct this was to add capacitance to the output. This was not very helpful and calculations showed that it would require 2-3 Farads of capacitance to fully clean up the output. The final solution was to design new electronic control circuitry.

2. WATER COOLED TEST BLOCK

Primarily used to make stationery welds but also to make some full penetration welds.

3. OSCILLOSCOPE

A 100 MHz, three channel scope was attached both to the welding power supply and welding torch. The excitation current pulse could simultaneously be compared to the small arc voltage signal caused by weld puddle oscillations. This was a very effective tool as it could be clearly observed that fundamental movements in the weld puddle could be seen on the screen. This remained the major research instrument until later in Level II when a computer was installed.

4. EXTENDED RANGE VIDEO (ERV)

Use of the video system was expected to be a key tool in developing **EDAP**. This turned out to be true particularly during Level II research. Much time was spent on selecting filter and lighting combinations for viewing the puddle.

5. SIGNAL FILTERING

Multiple frequencies simultaneously were observed on the oscilloscope screen. In order to better observe the Natural Frequencies (f_N) of the weld puddle the need for a signal filtering system being apparent, a system was designed and built.

To remove high frequency noise from the arc voltage signals arising from sources such as plasma noise, power supply interference and other sources, a 4th order Butterworth low pass filter was constructed. This was then placed in the **EDAP** signal collection system. The corner frequency of this filter was selected by considering the work of Renwick and Richardson (Ref. 5) and that of Zacksenhouse and Hardt (Ref. 7).

Renwick observed Natural Frequencies (f_N) on stainless steel, of 150-300 CPS in puddles having a size of approximately .04 in^2. Extrapolating Renwick's straight line fit to our expected puddle sizes yielded a resonant frequency of 85 CPS. In the theoretical model derived by Zacksenhouse, the predicted puddle vibrations were approximately 10 CPS. In view of those observations (Renwick and Zacksenhouse), a 3rd corner frequency of 200 Hz was selected. The arc voltage signal is first input to a different detector circuit to allow a ground point to be established prior to filtering the signal. (This filter was later modified for the Level II Research.)

The filtering section of the signal collection system has simplified the task of identifying the natural frequency of the puddle by removing noise which masked the puddle vibration effect.

B. PROCESS VARIABLES

Because a completely new set of welding conditions and parameters may be required for Welding A710 steel and developing the **EDAP** System, it was necessary to determine the limits of process variables. These efforts began as routine, based on published information and past experience. However, the GTAW process with 3/8" thick A710 steel presented some unique problems. Most of the tests in this portion of the work were done in combination with each other as each affected the final outcome. The individual results are reported.

1. TRAVEL SPEED

Initial pulse welding tests optimistically were started at 10 I.P.M. It was immediately recognized that this was far too high. A new gear box was installed on our travel carriage providing a minimum travel speed of 6 I.P.M.

Tests during this Level I research indicated that full penetration welds on 3/8" A710 plate was a difficult task. These early tests indicated that good arc signals could sometimes be obtained at speeds of 6 I.P.M. but the front wall of the puddle would cause constant interference with the arc signal response. Additionally, contamination of the electrode with actual shorting out at the front wall made these speeds impractical. The maximum speed that 300 Amp - 400 Amp arcs could be run at was 2 I.P.M. Most of the tests at Level I research proceeded at this speed.

2. ELECTRODE TIP SHAPE

Previous research by Renwick and Richardson (Ref. 5) indicated a 45° vertex angle provided the best response from the arc. The problem encountered with this angle was that full penetration of the plate was <u>not</u> obtained.

Based on Chihoski's (Ref. 8) and Key's (Ref. 9) research, numerable tests were made using flatter angles to 120°. Penetration <u>decreased</u> at these angles which led us to complete a large number of test welds at various vertex angles. All vertex angles from 28° to 120° provided good arc voltage response for estimating Natural Frequencies (f_N) of the weld puddle.

Maximum penetration of 3/8" A710 plate was the major problem. This was solved using a vertex

angle of 30° with a .050" truncation. See section 5.0 for further details.

3. GASES

Argon, Helium and various mixes of the two gases were tested. Unlike reports by earlier researchers it was found that either gas and most any combination of the two would provide good response to small arc voltage changes.

Combined gas flows of over 80 CFH completely dampened puddle oscillation. Research welds were made with up to 60 CFH combined flows which allowed puddle oscillations to be observed.

30 CFH Helium with 15 CFH Argon was used for almost all of the remaining research because it provided maximum penetration of the 3/8" A710 plates.

4. ARC VOLTAGE

Various arc lengths from 11.5V to 20 Volts were tested both for signal response and weld penetration.

All arc lengths between 11.5V to 18V provided good small signal response.

Arc lengths less than 13V were buried below the surface of the plates and the electrode easily became contaminated. The minimum arc length at 250 Amps need to be 13V, 300 Amps 14V and 400 Amps 15V. Arc lengths about one volt higher are more practical and still provide good penetration levels.

5. CURRENT LEVELS

A great amount of difficulty was encountered trying to arrive at the minimum average current level that would provide full penetration in 3/8" A710 steel. (See paragraph D.3. in section 2.2.1, regarding joint types.) Two problems were encountered:

First, as current was increased the weld puddles increased in width and depth of penetration decreased with average currents above 350 A. This produced weld beads so large that it was believed they would be metallurgically unacceptable. In all probability grain growth would be very large

resulting in poor physical properties. This seems to have some agreement with Chihoski's work relating to electrode shape (Ref. 8).

Second, welds that produced these very large beads had very broad widths up to 1". These wide beads had frequency responses that seemed to remain nearly the same up to 550 Amps. This suggested the possibility of a plateau of usable response for early **EDAP** development.

6. TORCH ANGLE

Tests for best torch angles were conducted for primarily determining what angle would be best to avoid the front wall effect and still provide good small signal arc voltage response.

Lead angles of up to 15° provide excellent signal response but did little to solve the front wall problem. Some lead angle is recommended to assure even gas flows and easy viewing.

Lag angles showed no improvement in signal response and the proximity of the electrode to the front wall appeared to be a potential problem.

7. WELDMENT CLEANING

The A710 plates had very heavy scale. Welding without removing this scale resulted in uneven beads, dirty slag surfaces plus poor small signal response from the arc.

For the continued research, all scale was removed from both the top and bottom of the plates in the welding zone. Edges were all sanded.

Before tacking together and prior to welding, the prepared surfaces were wiped with acetone to assure clean surfaces. It appears that all mating surfaces need to be sanded along with top surfaces to assure good weld quality and to obtain good small signal responses.

C. PULSE WELDING

The theory put forth by Renwick and Richardson, unlike Zacksenhouse and Hardt who used a sinusoidal pulse, contend that a sharp current pulse will cause the molten weld pulse to continue to oscillate at a fundamental frequency or Natural Frequency (f_N). One would intuitively believe a square wave pulse would be most effective in accomplishing this. Therefore, square wave pulsing was used for all research welding.

1. MILLI-PULSE (1-999 Hz)

A broad range of pulse rates were tested to determine what rates would, first, provide recognizable puddle oscillations and second, provide sufficient time to do frequencing estimates.

Fast pulse rates to 30 Hz appeared to provide recognizable responses from the puddle. These higher repetition rates were abandoned because in the large puddles encountered, oscillation frequencies appeared to be in the same range as the pulse repetition rates.

It was apparent that duty cycles of the MILLI-PULSE rates worked best when a long BASE current was selected. Duty cycles of 5% to 50% were tested. Long BASE currents to 100 ms provided sufficient time to do visual frequency estimates without losing much of the recognizable wave form on the oscilloscope screen. 80 ms BASE current time was used for most of the final research work.

It appeared during this Level I research that a 10-20 ms high current pulse did a very strong job of causing puddle oscillations, with little difference between these two levels. Therefore, most of the research work was done using a 20 ms pulse. (This was later found not to be the best excitation pulse width, see Level II 2.2.2,B-5.)

2. MICRO-PULSE (1 K Hz to 50 K Hz)

Near the completion of the Level I research MICRO-PULSE was superimposed on the MILLI-PULSE. Various rates between 690 Hz and 16,430 Hz were tested. MILLI-PULSE rates of 11-25 Hz at 20% to 50% duty cycle were used. This had a dramatic effect on smoothing out the wave forms observed on the oscilloscope. At no time did the superimposed MICRO-PULSE interfere with the observed Natural Frequencies (f_N).

3. PULSE AMPLITUDE (IP_e)

Amplitude of the excitation MILLI-PULSE was tested from 50 Amps to 200 Amps above BASE level, 50 Amps being the lowest level that Renwick and Richardson (Ref. 10) believed necessary to start the puddle into motion. (This level was 50% of their BASE current). It was expected that our much larger weld puddles might require larger amplitudes, perhaps with longer pulse widths. It was determined that the MILLI-PULSE excitation amplitude did a strong job of causing puddle oscillations in the 100 Ampere area, for 250-500 Amp welds. (Note: At the end of the Level II research this amplitude was found to be too high. See Level II 2.2.2,B-4.)

4. MECHANICAL EXCITATION

To determine if the observed puddle oscillations were not just the result of the electrical circuits or test equipment, tests were run using mechanical excitation.

An ordinary hand hammer was used to hit the plates being welded. This was done both as single impact and in one second repetitions. When the oscilloscope screen was observed the same arc voltage changes were seen. These were estimated at the same frequency levels as when a current pulse was used to excite the weld puddle. Different puddle sizes would develop different frequency rates that appeared in the expected direction of lower frequencies for larger puddles.

D. WELDMENTS

1. A710 STEEL PLATES

Most welding initially was performed on 3/8" thick HSLA A710 steel. (See Appendix A for analysis.) A larger number of experiments were run trying to get full penetration welds with pulsed welding currents, for both bead-on-plates and tight butt joints.

Bead-on-plate welds would inconsistently provide full penetration with reasonable weld bead shapes. Plates 3/8" thick would sometimes have welds with top bead 3/4" wide and sometimes 1/2" wide, run at identical welding parameters.

Tight butt joints on the same 3/8" thick plates would only occasionally provide full penetration. Almost all of these high current welds would result in very wide top bead widths of 3/4" to 1" wide. Rarely did a wide top bead weld provide full penetration. It was finally decided to machine some of the 3/8" plates down to 1/4" and 3/16" thick. Some full penetration pulse welding experiments were repeated. Consistency of weld size and shape improved substantially.

As it was impractical to machine down all of the A710 plates on hand to continue the **EDAP** research, it was decided to do some testing on mild steel plates.

2. MILD STEEL PLATES

Because of the difficulties in producing full penetration welds in the A710 plates, it was finally decided to repeat some of the same pulse welding tests on mild steel plates.

3/8" thick mild steel plates also showed some inconsistencies in penetration and top bead width. Bead on plates were more consistent than tight butt welds.

1/4" thick mild steel plates were very consistent in weld bead size and penetration, both bead on plate and tight butt joints.

3/16" thick mild steel plates welded excellent.

Since one of the purposes of this research was to develop **EDAP** using single pass, full penetration thick root welds, it was decided to continue **EDAP**

weld testing primarily with 1/4" mild steel plates. Frequently the parameters for the mild steel tests were repeated on A710 plates to determine if there were any differences between welding of mild steel and A710. A710 plates did not provide the same consistency in weld bead shape as mild steel; however, the A710 was borderline acceptable.

3. WELD JOINTS

The difficulties encountered for welding the 3/8" thick A710 plates led to experimentation with various joint sizes and types using pulse welding.

Providing gaps of 1/32" to 1/8" wide for square butt welds again resulted in very inconsistent weld bead shapes and penetration. In fact **it was determined that having a gap reduced the amount of penetration for pulsed welds.** (There was no comparison made with steady DC welds.)

Prepared joints using various "V" groove sizes and land thicknesses were also tested for pulse welding A710 steel plates. These tests included both tight butts and leaving gaps. The same difficulties were encountered of inconsistent bead shapes and penetration.

These continued problems of welding 3/8" A710 steel helped led to the decision to use 1/4" mild steel plates for **EDAP** development.

4. ALUMINUM

Some brief tests were made on aluminum plates to see if puddle oscillations could also be observed. These preliminary tests indicate that fundamental oscillations also exist in aluminum weld puddles.

5. FILLER WIRE

A considerable amount of investigation was made for finding a filler wire for A710. At this time there appeared to be none manufactured in the United States. The best filler wire that could be located, that would nearly match the base metal physicals and chemistry, were two submerged arc wires. We had them specifically drawn down to .045" for us. See Appendix B. Filler wire additions were not used in either Level I or Level II research becasue of time restrictions.

E. CONCLUSIONS LEVEL I RESEARCH

Level I Research ended with the following conclusions:

1. A current pulse will excite the weld puddle into fundamental oscillations.
2. There is good correlation between puddle size and puddle oscillation frequencies in large weld puddles.
3. A discernable step (increase) in both voltage level and amplitude of the observed wave forms is seen when full penetration occurs.
4. A710 steel behaves differently than mild steels to the pulsed GTAW process.
5. Large welds react much differently to the pulsed GTAW process than small welds on A710 steel.
6. The video system (ERV) is a valuable research tool, but could use more development to apply it to its full potential.

2.2.2 LEVEL II RESEARCH EDAP

A. EQUIPMENT

With the feasibility of the EDAP concept established during the Level I Research, a more sophisticated research program was designed and implemented. Primary to this next level was the addition of a scientific computer. This provides precise data processing with the capabilities of being able to perform as a control center for the welding power supply. See Figures 1, 2 and 3 for the final research set up.

Mild steel plates were primarily used during Level II Research, with some of the results compared by again welding on A710 steel.

1. Fixture - A complete test welding fixture with a travel carriage was designed and manufactured. Features include a conforming grooved back-up bar, that pneumatically presses against the back side of weldments. The back-up bar is cooled with CO_2. The main feature of this fixture is the quick clamping and release which provides the capability of making test welds rapidly without significant set up times.

2. Optical Viewer - An ARCON Model 900 arc viewer was installed for continuous close viewing of the arc and puddle. High magnifications of up to 8X were used. This unit was particularly very helpful in maintaining arc length and magnetically positioning the arc to avoid "Front Wall" effects, start and stop points, along with monitoring and adjusting the centering in the joint of the electrode.

3. Fibre Optics Viewer - was used initially to provide a different angle of view than the optical viewer and video CRT screen. This was abandoned because of the poor resolution by fibre optics.

4. Scientific Computer - Because of the difficulty in performing precise weld puddle oscillation frequency calculations it was determined a high speed computer was needed. Such a computer could also be used to control the welding machine in real time.

5. Magnetic Arc Positioner and Stabilizer (MAPS) Used to overcome arc blow problem and to preposition the arc.

FINAL RESEARCH SYSTEM BLOCK DIAGRAM

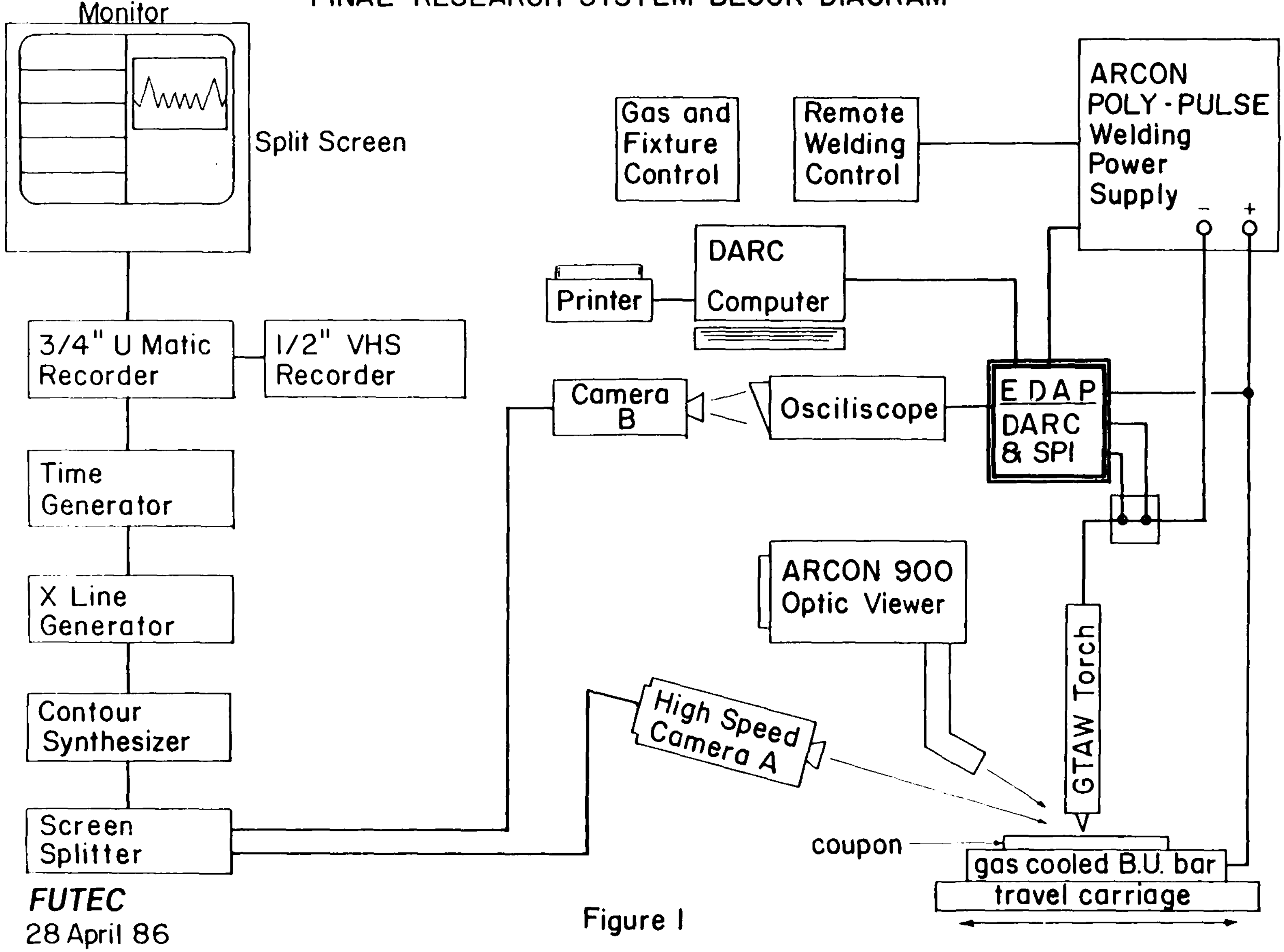
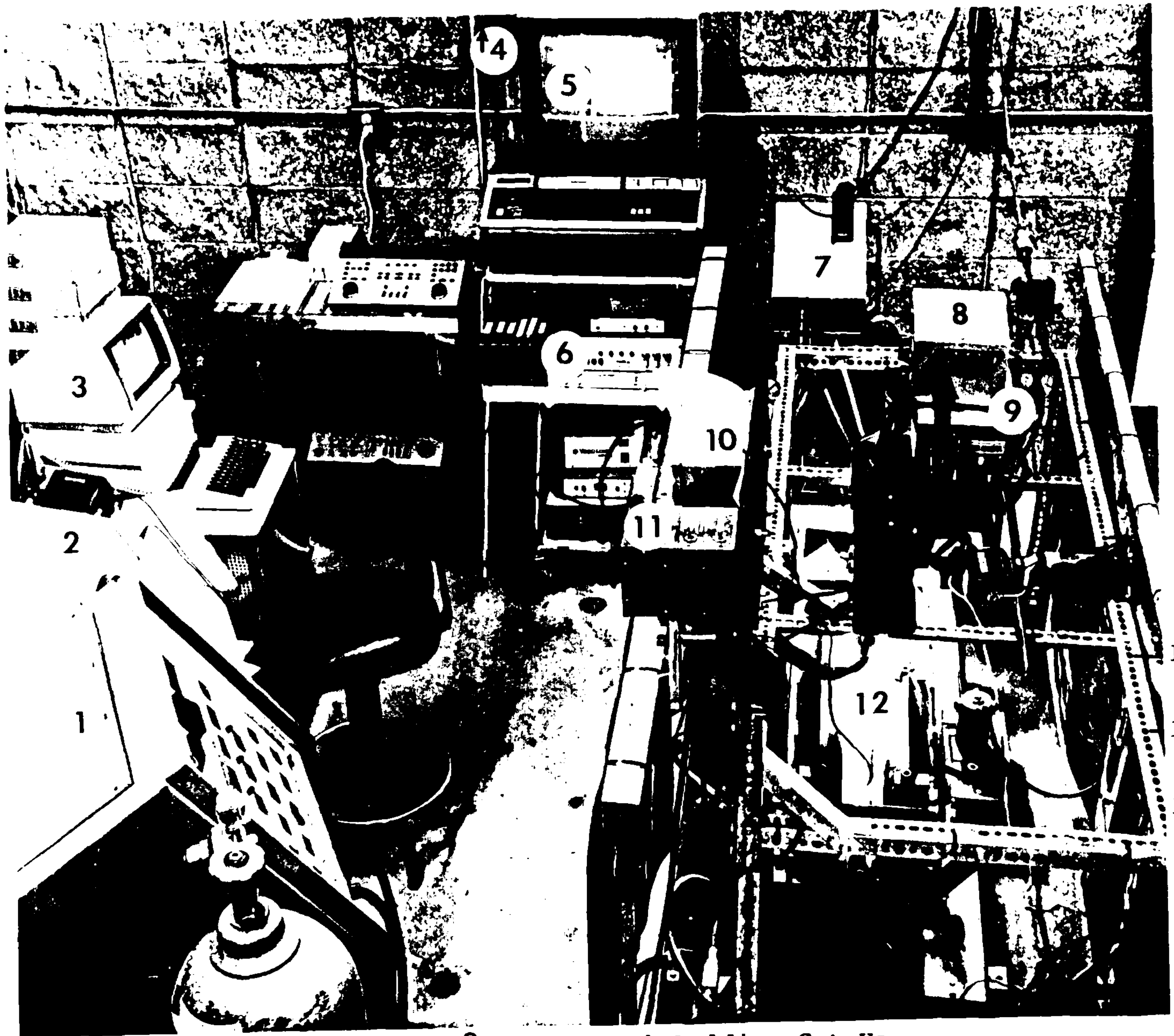
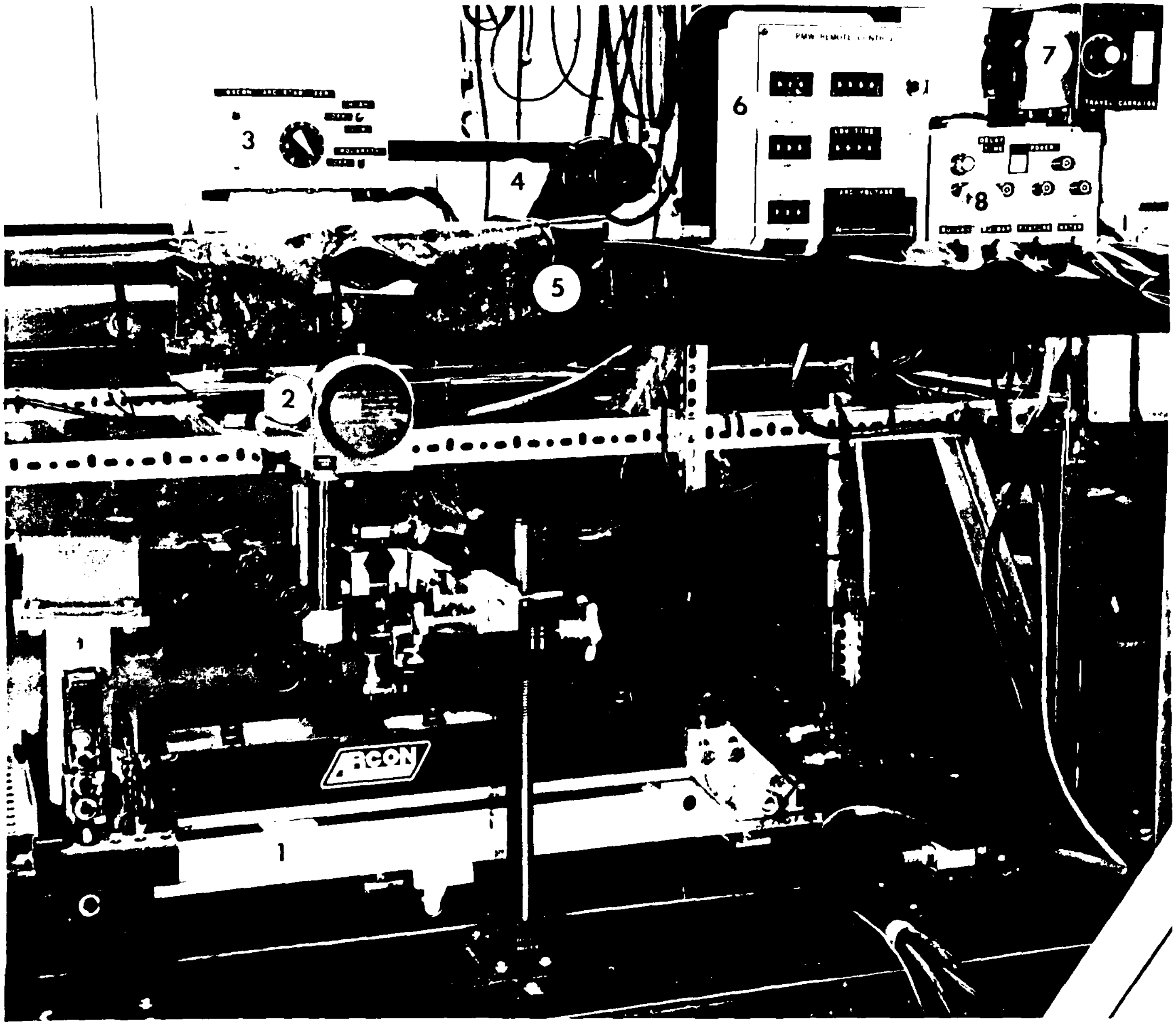


Figure 1



1. ARCON POLY-PULSE Welding Power Supply
2. Oscilloscope
3. DARC Computer
4. Video Camera (Oscilloscope Screen)
5. VCR - Split Screen
6. Video Accessory Controls
7. High Speed Video Camera
8. Magnetic Arc Control
9. Cold Wire Feeder
10. Welder Remote Control
11. Travel Carriage Speed Control
12. Travel Carriage

Figure 2 Research Welding Set Up



1. Welding Fixture
2. Optical Arc Viewer
3. Magnetic Arc Control
4. Cold Wire Feeder
5. Timers
6. Welder Remote Control
7. Travel Carriage Speed Control
8. Sequencer and Fixture Controls

Figure 3 Research Welding Set Up

B. **EDAP** WELD TESTS

The addition of the scientific computer to our research system was deemed necessary to accurately assess the events that were happening in the weld puddle as picked up through the arc. The computer system is described in Section 2.3.

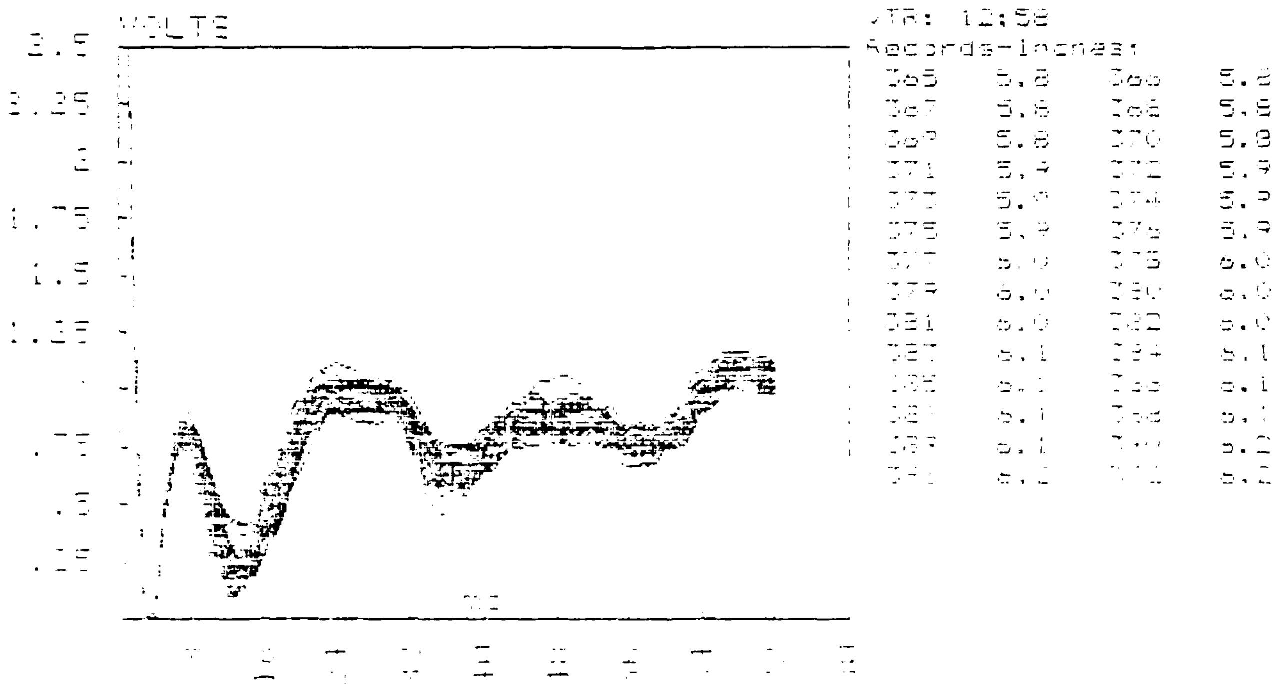
Level II research procedures included recording the data for each weld on an individual computer disc. Most of the final welds made each have their own disc, which can be recalled for continuing analysis. This allows modification of estimation software without repeating welds. During the weld, changes can be made in the weld parameters such as background current, excitation pulse amplitude, excitation pulse frequency and duty cycle and weld travel rate. To allow time alignment of the weld pool oscillation data with changes in weld parameters, a reference (record) number is displayed on the computer screen at all times and recorded at the time of any weld parameter change. All of this information is on computer disc.

Initially the computer was used to estimate frequency data by plotting a hard copy of the arc voltage wave forms, similar to what is seen on the oscilloscope. Using the computer printer to overlay multiple wave forms on each other, the consistency and repeatability of puddle oscillations could be observed. See Figure 4 wave form plots of part of weld 12:58. These were some of the early wave forms generated by the computer system, which confirmed the observed oscilloscope wave forms and their relationships to welding parameters. (See Figures 10 and 11 for additional analysis of this weld.)

These wave form plots also were used in filter development and confirmation of later frequency estimation checks.

Most important, a variety of wave forms would be produced that did not agree with what was expected during changes in welding parameters. This was the same difficulty experienced in viewing the oscilloscope wave form displays. This use of the plotted computer generated wave forms, proved unequivocally that there were some other very serious problems for consistently producing weld puddle oscillations, that are repeatable and useable.

ARC VOLTAGE WAVE FORM PLOT
Computer Generated



Background Current Time

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Figure 4

1. The first discovery was the effect of arc length in collecting data for the computer. Very short arc lengths (11-15V), desireable for providing maximum weld penetration, provided the most fluctuations in voltage. However, these fluctuations contained so many variations that accurate frequency estimations were difficult and distorted. Using longer arc lengths (14-15V) solved this problem, with the arc acting as its own filter and averaging device.

2. The second discovery was the condition of "Start Effects" and "End Effects." "Start Effects" were anticipated. As would be expected a nominal settling time was required for obtaining usable information. However, the "End Effects" were found to occur as early as three inches before reaching the end of the plates. For most of our test welds this was two inches from the end of the weld including the final craters. Very large welds made by high currents of 400 to 600 Amps had the most severe problems with the "End Effects." Lower current welds would encounter the "End Effects" closer to the end of the test plates. For example, a 300A weld would exhibit "End Effects" two inches from the end of the plate or one inch from the end of the weld, including the crater.

   We have not determined what all of the causes of the "End Effects" might be. However, it is possible that a heat dam causes some changes in the puddle (as described by Chihoski, Ref. 11). Another possibility might be that arc pulsing frequencies are disturbed by the end of the plates and weld puddle oscillations may be attenuated.

3. Additionally, "Secondary Wave" forms were observed. These wave forms were at higher frequencies than the primary wave forms. It is expected that these disturbances exist primarily on the surface of the weld puddle. The third discovery was that these wave forms could be reduced significantly by superimposing MICRO-PULSING on the MILLI-PULSE rates being used. All rates of MICRO-PULSING appeared to remove these secondary waves. Test welding would have continued with superimposed MICRO-PULSE if our filtering system and frequency estimators were designed to compensate for this condition.

4. **The fourth and most important discovery in this research was what we believe to be a "Traveling Wave"** or what is sometimes called a "bow wave." This wave on the welding puddle is large. This large wave sometimes moves toward or away from the electrode, distorting oscillation wave form plots and frequency estimations. This was the primary problem in producing reliable information to use for later controlling a welding system. This is a high energy wave which is interpreted by the computer as a very low frequency oscillation.

   By reviewing video tapes of the welds and comparing them to the computer generated wave form plots, their existence was confirmed. Replaying the video tapes at higher than normal speeds clearly showed these moving wave forms.

   By continued experimentation a method was found to control these "Traveling Waves." It was determined that the excitation pulse amplitude was the primary cause of "Traveling Waves." When the amplitude of the background current was above 90 Amps the wave was almost always present. When the amplitude was below 70 Amps a "Traveling Wave" was <u>not</u> observed.

5. An important change to the Level I research was the determination that the excitation pulse or MILLI-PULSE "High Time" was causing problems in consistency of puddle oscillations. The earlier tests indicated very strong wave form production when a <u>20 ms</u> pulse width was used. There eventually was concern that this time was too long causing dampening of the puddle oscillations.

   A large number of experiments were run using a <u>10 ms</u> width for the excitation pulse with much improved consistency. However, there were still some inconsistencies in wave form observations and it was decided to run another group of experiments for determining the best excitation pulse width. Excitation pulse widths from 1 ms to 30 ms were tested. It was determined that pulse widths of between 2 ms to 4 ms provided the most consistent response. All final welds were made using this range.

C. FREQUENCY ESTIMATION

Precise frequency calculations were difficult using the Wave Form Plots only, but were more readily accomplished than just using the oscilloscope wave forms. Overlays developed by the "Wave Form Plots" clearly showed the repetition of the puddle oscillations indicated continuous frequency estimating was a probability. Therefore, software was developed for computing frequency estimates and then plotting them for the entire weld length. See Figure 5, Section 2.3-C and Appendix F for a complete description.

The "Computer Generated Frequency Estimates" as illustrated in Figure 5 provide many capabilities:

1. The scale across top indicates a record number on the computer disc. Each number relates to a precise position in the weld.

2. The vertical bars are positioned by the computer operator, typically to locate the areas of parameter changes. This was also used to mark significant points of interest. Notice that this bar carries with it the exact weld position in inches and the record number used for automatic location.

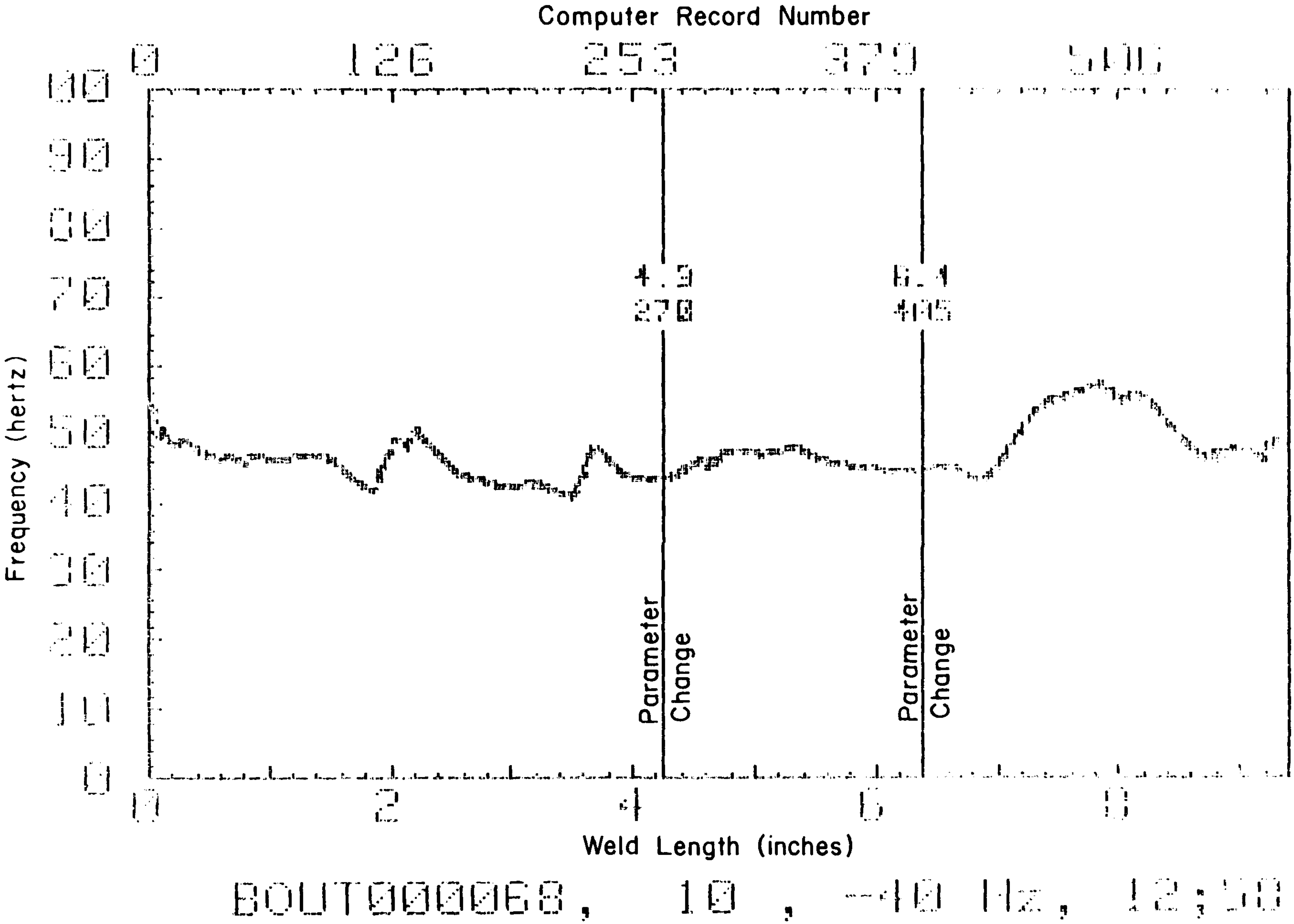
3. The frequency scale provides indexes for the puddle frequencies as estimated by the computer.

4. The bottom scale plots the length of the weld in inches.

NOTE:
Most of the research welds were made 8 - 9" long. The size of this plot allowed alignment of the hard copy printout directly with the weld sample. Therefore, the correlation between oscillation frequency estimates and penetration could be made by direct comparison. No measuring or estimating needed to be done by the researcher.

D. RESEARCH WORK SHEETS

Completed for every weld was a work sheet (see Appendix C). These work sheets provide permanent records for historical purposes and tie together each computer disc, Wave Form Plot, and Frequency Plot with a time index on the video tapes.



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COMPUTER GENERATED FREQUENCY ESTIMATES

Figure 5

E. MAGNETIC ARC CONTROL

It was decided that a significant number of improvements might be made by magnetically controlling the position of the welding arc in relationship to the electrode and weld seam. A two pole electromagnet with control was designed and built.

1. ARC BLOW

Several arc blow problems were first encountered during Level I research on A710 plates. These were thought to be possibly overcome by using a magnetic arc stabilizer. Arc wander was significantly reduced but not completely eliminated.

The new welding fixture is made of almost 100% non-ferrous materials; therefore, the fixture was not believed to contribute to this problem. Various test welds were made for testing ground cable locations. The final location was directly on the copper back-up bar with the welding direction away from the ground. It is uncertain whether or not this was of any benefit.

Weld tests were then conducted on mild steel plates 1/4" thick. No arc blow was encountered on these plates with the magnetic control in place.

Further tests on A710 plate were made at various current levels. **It was found that the higher the current levels the more the arc wanders.** This, of course, is opposite to what is encountered in normal GTA welding. One can only suspect this situation is the result of welding on A710 steel. (A similar effect on welding on HY80?)

The following is offered by Woods and Milner (Ref. 12):

> "The resistance heating creates a local increase in temperature of the molten metal. Since the resistance of molten metal increases with temperature it becomes increasingly more difficult for the current to follow this path. Thus the current is continually seeking out fresh paths, the 'hot spot' moves around, and the motion associated with the concentration of current becomes erratic."

The authors indicate that these Lorentz force problems are more severe on thicker plates.

Level II research included machining down A710 plates to reduce the thickness. Arc blow was almost eliminated in these tests. They were also welded at reduced current levels. It is reasonable to conclude that in welding thicker sections of A710 plate at high current levels, severe arc blow can be expected.

2. Magnetic Arc Positioning

Two problems are encountered when welding thick sections, at high current levels and travel speeds.

First, is contamination of the welding electrode due to its close proximity to the front wall of the weld puddle. There are three possible solutions to this problem.

a. Weld more slowly (and at lower current levels). This was considered unacceptable from a practical standpoint. A standard of a minimum of 4 I.P.M. welding speed was established. By forcing the arc plasma forward with the magnetic arc control, the front wall no longer limited travel speeds.

b. Use very long arc length. This was considered unacceptable as penetration decreases and the weld bead widens considerably. Prepositioning the arc has the advantages of increasing penetration at the same travel speeds and welding parameters.

c. Weld thinner plates only. This would provide a condition where the electrode would remain above the top surface of the plate. This, however, would not meet the purposes of this research for welding root passes in thicker plates.

Second, is the effect the front wall has on data collection. When the arc plasma is very close to the front of the puddle it interferes with the signal provided by the weld puddle. Prepositioning the arc, forces the front wall ahead and the electrode is more centered over the puddle. Prepositioning the arc provided good puddle signal response for the operation of **EDAP**.

3. Penetration Control

There has been some previous research concluding that using a strong magnetic field in the presence of an arc decreases penetration. (Refs. 13 and 14) A series of welds were made to test this, as it was considered necesary to use the magnetic arc control for the remainder of this research.

Tests were performed for pulsed arcs, with the arc both centered directly under the electrode and positioned ahead of the electrode at varying amounts.

a. For the centered arc, depth of penetration remained the same regardless of field strength.

b. For the prepositioned arc, penetration increased with increasing magnetic field, see Table 1. Notice also that area also increased, possibly due to the more efficient constricted arc caused by the magnetic field.

MAGNETIC ARC CONTROL (MAPS)

Prepositioned Arc

POWER	DEPTH	WIDTH	AREA	SHAPE
100%	.32 in.	.60 in.	.43 $in.^2$	C/
75%	.25	.62	.39	C//
50%	.22	.65	.38	C//
25%	.20	.60	.35	C//
0 Control	.23	.60	.37	C//

$$\frac{\text{Area}}{\sqrt{\text{Width} \times \text{Depth}}}$$

A710 Steel 3/8" Tight Butt

P_e^+...........499A.....20 ms
Background....399A.....80 ms
Voltage.......14-15
Travel........4 I.P.M.
Gases ....He 30 + Ar 15, cfh

NOTE: Weld puddle was excited into oscillation by a 100 Amp excitation pulse (P_e^+)

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Table 1

F. NOTCH FILTERING

EDAP research software, as designed, has the capability of removing from the frequency estimation routine various frequency levels. As there might be possibilities of harmonics distorting the frequency estimates, such notch filtering was tested. No significant value was found using filtering for harmonics. Both wave form plots and frequency estimation plots remained nearly the same.

G. EXCITATION PULSE REPETITION RATES

The sensitivity of the **EDAP** System to various pulse times need to be considered. Testing was done at various duty cycles and pulse widths.

Good, clear wave forms were produced when background current times were under 100 ms. Puddle oscillation frequencies for the size of puddles tested could be accurately estimated with a 8 - 10 ms delay, with total widths up to 80 ms. Wave forms began to become slightly distorted beyond 40 ms with considerable noise and variances at 100 ms.

As could be expected, the highest energy puddle oscillations are found immediately after the excitation pulse. Therefore, early wave forms have less chance of being disturbed by other processes, weld puddle conditions or external influences such as mechanical vibration. These strong and consistent wave forms provide all of the frequency estimation data in the first 60 ms, to enable a control signal to be developed. Lower pulse repetition rates may scatter the data for the **EDAP** frequency estimation routine and therefore make it less accurate.

During these experiments tests confirmed that superimposing MICRO-PULSE on the BASE current eliminated the secondary wave forms while slightly reducing the amplitude of the fundamental wave forms or Natural Frequencies (f_N).

H. BASIC TEST WELDS

With almost all of the Phase I research completed, wherein many changes were made in welding procedures and conditions, it was deemed valuable to repeat some of the basic initial experiments. This was done using the research computer and software. This was to precisely confirm that there is a fundamental movement in the weld puddle that could be initiated by an excitation current pulse. Also that the Natural Frequency (f_N) varied with puddle size.

These basic tests repeated, ranged from stationary welds to beads on plates, at various current levels. This also included repeating welds on copper plate wherein no puddle existed. These efforts reconfirmed the basic principles involved and our computer system's ability to recognize and identify the fundamentals of the **EDAP** concept.

Additional welds were made to confirm the effects of having an unsupported full penetration weld versus a supported weld. Unsupported welds were those that had no back up, i.e., the plates were suspended in air. Supported welds had 1/16", 3/32" and 1/4" groove depths. There were no noticeable differences in frequency observations. **It was observed that the amplitudes of the puddle oscillations increased as backside support decreased.**

Because there is a problem with making very large welds unsupported, most of the **EDAP** test welds were made using a copper back-up bar having a 1/16" deep by 1/2" wide groove.

I. INVERTED PULSE (P_e^-)

During the repeating of the basic welding experimentation E. above, the original Kotecki (Ref. 9) experiment was performed. This is where the arc was extinguished and fundamental frequencies observed. This produced the expected wave forms normally developed by puddle oscillation.

Extending this principle still further, it was decided to repeatedly turn off or reduce the arc current momentarily on a repeated basis, and then observe fundamental puddle oscillations. The results were similar to the puddle oscillation rates observed with the increasing current pulses (P_e^+).

This **major discovery** led to additional experiments. Many of the previously tested variables were again tested in a limited number of welds. Preliminary results indicate that this method of puddle excitation (P_e^-) is less sensitive to the previously studied variables such as arc voltage, pulse amplitude, pulse width and travel speed. **Inverted pulsing (P_e^-) appears to provide a more stable EDAP environment.**

Most important was that large excitation pulse amplitudes to 100 Amps, did not appear to cause the "Traveling Wave" effect. Pulse amplitudes were successfully tested from 40 to 100 Amps.

Excitation pulse widths were tested from 1 ms to 30 ms. Again excellent frequency response was developed at widths of 2 ms to 30 ms. When excitation pulse times were long, over 10 ms, the puddle oscillation wave forms could be observed during both high (BASE) and low current times. This confirms that puddle motion can be initiated and sustained by either the leading or trailing edge of the puddle.

This may be of help for the further development of the **EDAP** system.

Of significant importance to field applications, it appears that high travel speeds can be used under this pulsing condition (P_e^-). Welds were made at speeds up to 6 I.P.M. (a gear box limitation). There was no observable deterioration of wave form produced by puddle oscillations.

As the **EDAP** system was not designed for this negative going pulse; therefore, computer documentation was not produced. This discovery was made at the very end of Phase I research. Time constraints limited any modifications to our **EDAP** system hardware or software.

2.2.3 EDAP TEST WELDS ANALYZED

The following is part of the data collected during some of the test welds run during EDAP research. These plotted results were selected to illustrate the potential of EDAP to provide nugget size and penetration control. (No attempt to control the weld puddle oscillation frequency was made on these welds. EDAP was being operated in an observation mode only.)

This data was originally obtained using the algorithm outlines in Section 2.3 where there was a significant amount of scatter. To more accurately observe changes in the estimates, a finite impulse response lowpass filter was applied to the series of frequency estimates.

Manual control of both voltage (arc length) and current was used. Therefore, in the plots of all welds, one can see perturbations in the plotted data wherever any deliberate changes in current or voltage were made, or any corrections in arc length to control voltage. (Speed was held constant throughout all welds.)

There are also "Start" and "End" effects for each weld. "Start Effects" require a settling time of perhaps 1" of weld at 4 I.P.M. travel speeds. There are two sources of "End Effects". The first is just the shutting down of the arc when final currents and voltage are sensed. The second might be due to the heat dam caused by reaching the end of the plates.

The selected welds that follow clearly illustrate the information received back from the weld puddle. **Data is very distinguishable and operates in a direction which proportionally shows weld nugget size. Most important, full penetration welds with an excellent correlation to root bead widths, are detectable by the frequency estimates.**

WELD 15:30

An unsupported stationary weld made on 1/2" steel plate.

The starting BASE current was maintained at 200 Amps for approximately 40 seconds after which the BASE current was increased to 350 Amps. The weld reached full penetration at 42-55 seconds. Finally the arc blew through the unsupported puddle at 56 seconds. The excitation pulse (P_e^+) amplitude (IP_e) was maintained at 100 Amps above the BASE current throughout the experiment. It was observed on the oscilloscope screen that **the amplitude of the puddle oscillations increased when the weld puddle reached full penetration,** then continued to get larger until blow-through occurred. Frequency of the oscillations remained approximately the same with perhaps only the increases as shown in Figure 6(A), just prior to blow through.

Figure 6(A). This is a plot of the estimated weld puddle oscillation as the weld progresses in time. Note the gradual decrease in frequency as the weldment builds up heat while the puddle size increases. The vertical bar at 40 seconds into the weld indicates the area at which the current change was made. At this time we see the frequency estimates dip indicating an increasing puddle size. The time at which the weld burns through is immediately obvious in the frequency data. A sudden increase in the estimated frequency is seen. This is probably due to the fact that the puddle is not uniform if indeed the concept of a puddle is appropriate at burn through. The data presented in Figure 6(A) was estimated using a frequency window of 50 to 117 Hz. That is, only frequencies in this region were considered when calculating the estimates of the puddle frequency.

Figure 6(B). This plot shows the frequency estimates if a window of 0 to 117 Hz is used. When employing the larger frequency range the characteristics are not as easily identifiable. There is still a trend of decreasing puddle oscillation frequency up to a short time before the current change. Here the estimator apparently loses track of the puddle size. The burn-through point is still readily identified and perhaps predictable.

WELD PUDDLE OSCILLATIONS

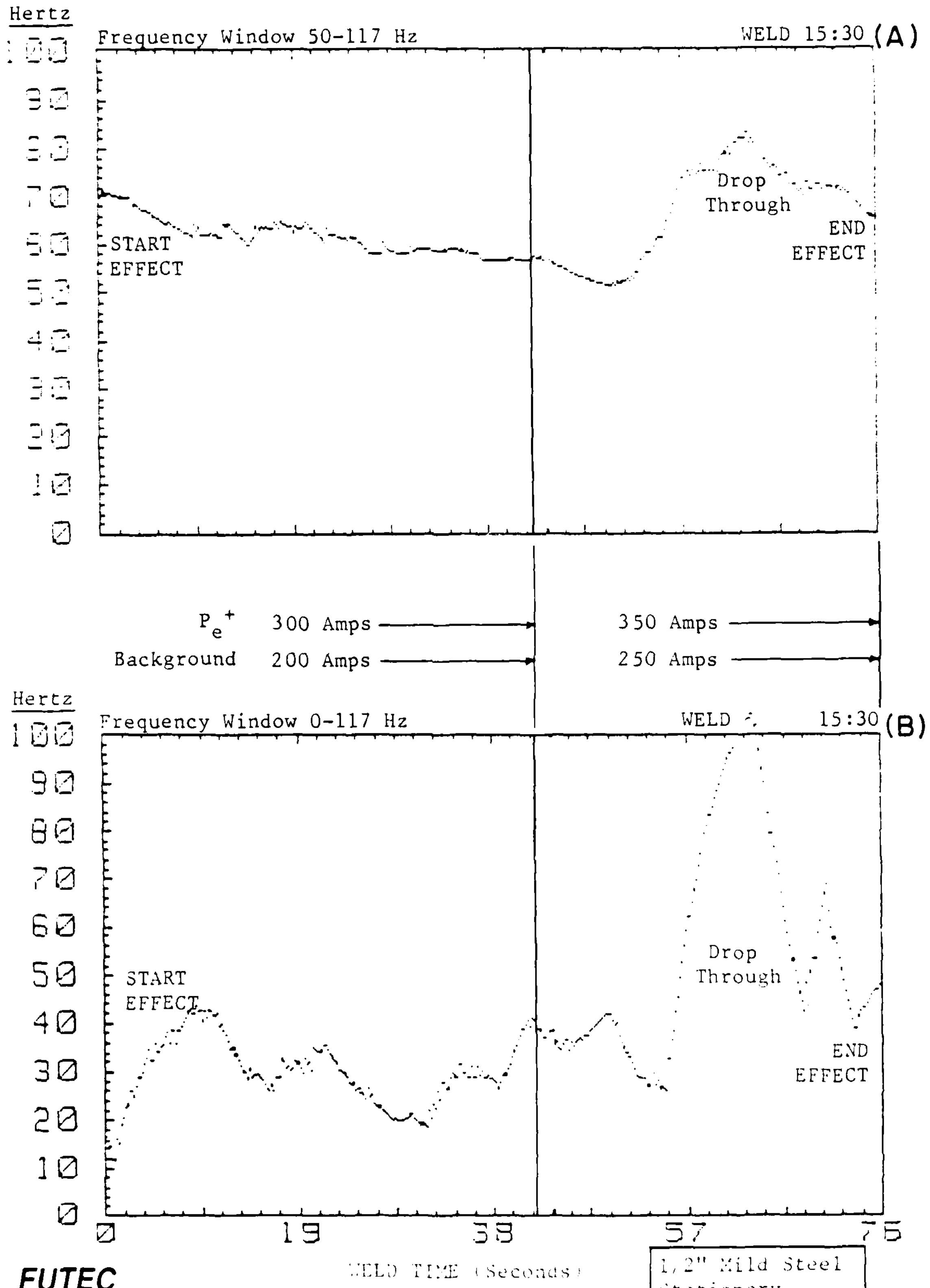

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Figure 6

WELD 14:03

Tight butt weld on 1/4" mild steel plate at 4 I.P.M. Excitation pulse width (P_e^+) of 10 ms.

Welding was started at 279 Amps with an excitation pulse (P_e^+) to 329 Amps. Approximately half way through the weld the BASE current was reduced to 279 Amps. The weld had heavy full penetration up to the time of the current change. After the current change only partial penetration was achieved.

Figure 7 is a plot of the puddle oscillation frequency estimates obtained as the weld progressed. The frequency is quite stable through the first half of the weld reflecting the constant current input and uniform heat absorption as the weldment travels under the arc. **At the point where penetration is lost the frequency of the puddle takes a dramatic step up** and then remains fairly constant for the remainder of the weld.

WELD 13:04

Tight butt weld on 1/4" mild steel plate at 4 I.P.M.

In this experiment the width of the excitation pulse (P_e^+) was varied keeping all other parameters constant.

Figure 8 illustrates the puddle frequency data taken during this weld. The vertical bars on the plot delineate the six regions where the excitation pulse (P_e^+) was changed. Initially, with a wide excitation pulse (P_e^+) there was heavy penetration through the plate. As the pulse width was decreased penetration was lost until the end of the weld, when the pulse width was increased once again. The frequency data reflects this information nicely. **The change in excitation pulse width affects the total heat input to the weld puddle.** The **EDAP** scheme now used adapts to this condition.

WELD PUDDLE OSCILLATION
FREQUENCY DATA

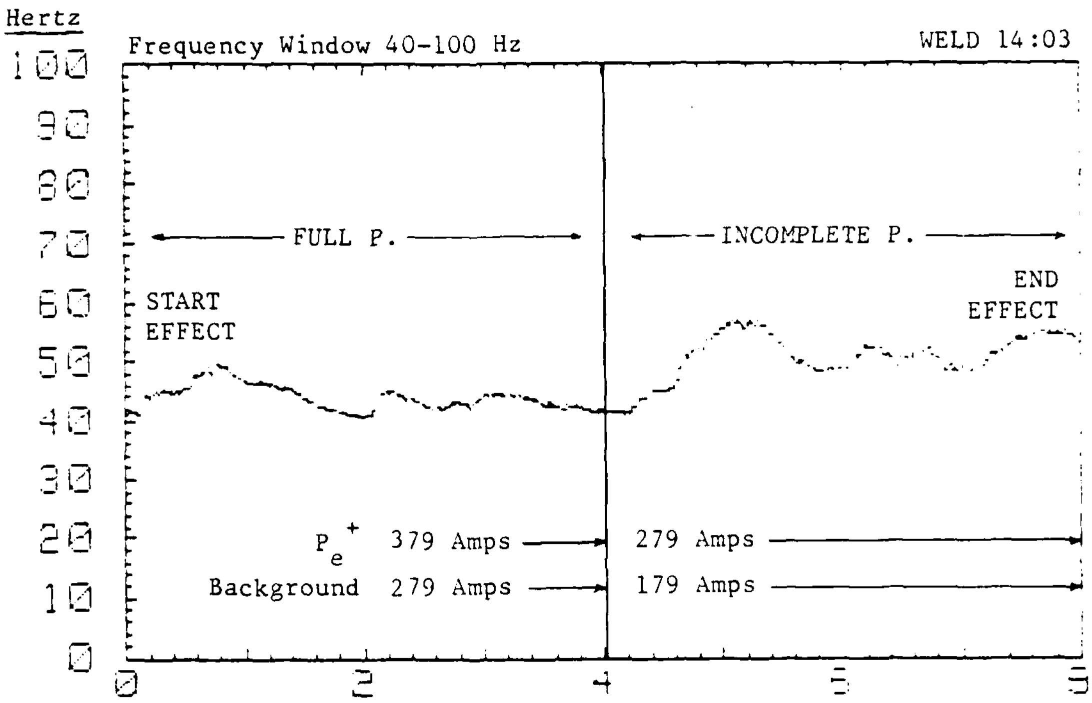

Figure 7

PUDDLE OSCILLATION DATA
EXCITATION PULSE WIDTH CHANGES P_e^+

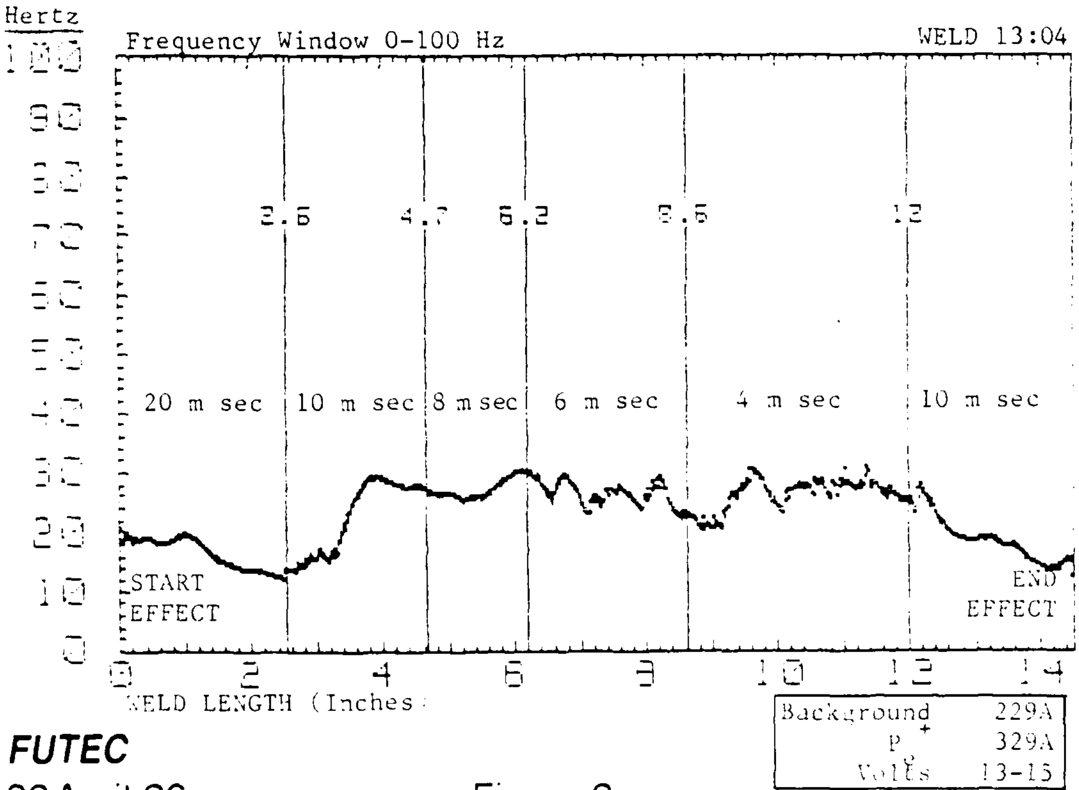

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Figure 8

WELD 13:51

Tight butt weld on 3/16" mild steel plate at 4 I.P.M.

The arc voltage was varied between 13 and 15 volts. BASE current was decreased with very small step changes from 139 Amps to 119 Amps. Excitation pulse (P_e^+) levels were 239 and 219 Amps respectively. The joint showed full penetration for the length of the weld with one spot of incomplete penetration at 10.6".

Figure 9. Figure 9(A) is a plot of the root bead width variation for the entire weld length. The other figures show the corresponding estimated puddle frequencies for windows of 0 to 100 Hz (Fig. 9B) and 50 to 100 Hz (Fig. 9C).

Notice the linear variation of the root width with weld distance. This variation is reflected in the weld pool oscillation data in the direction expected. That is, **a reduction in puddle size corresponds to an increase in frequency.** Another characteristic of the frequency data is the increasing trend is nearly identical in both the frequency windows. The average frequency from the two estimators is much different however. Notice also the 0 -100 Hz frequency window shows the trend toward insufficient penetration 10" into weld, to a point of no root penetration at 10.6".

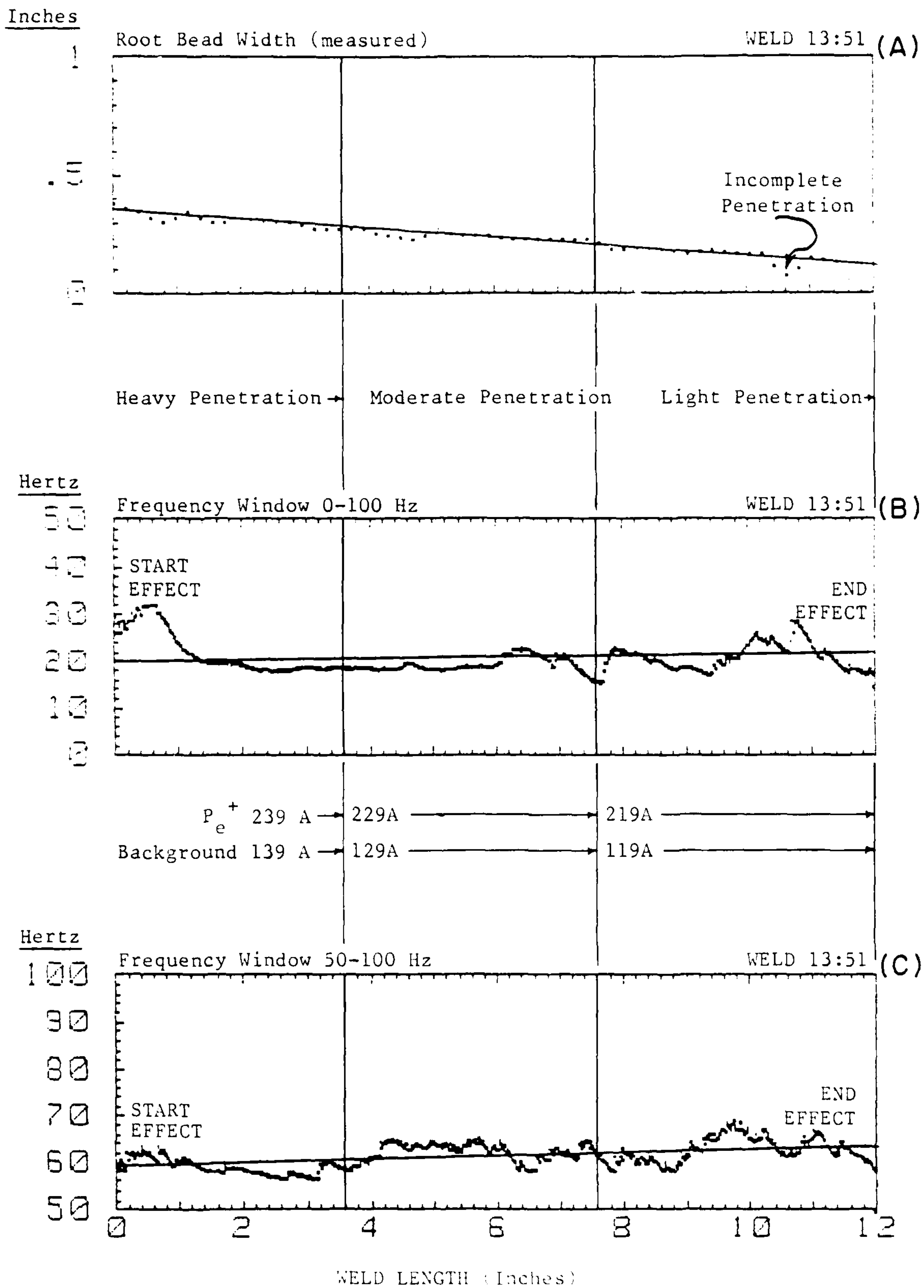

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Figure 9

3/16 Mild Steel
13-15 Volts
Travel 4 I.P.M.

WELD 12:58

Tight butt weld on 1/4" mild steel plate at 4 I.P.M.

For this weld the current was reduced three times where indicated by the vertical bars. The initial current of 249 Amps was reduced in steps to 199 Amps. The excitation pulse (P_e^+) was started at 349 Amps and was simultaneously reduced to maintain a 100 Amp amplitude.

The results of this test illustrate the perfect setting for a controlled weld scenario.

Figures 10 (A) and (B). This weld had good penetration for the entire length but rather large deviations in top and root bead widths as can be seen in Figures 10 (A) and (B).

Figures 11 (A) and (B). These are plots of the puddle frequency and the approximate volumes of the puddle (for convenience this assumes the puddle is shaped like a tapered cylinder). Notice the very good agreement in the data.

It is apparent that not only can the general trend of the puddle size be detected, but relatively short perturbations in the weld can also be measured and be compensated for.

BEAD WIDTH (MEASURED)

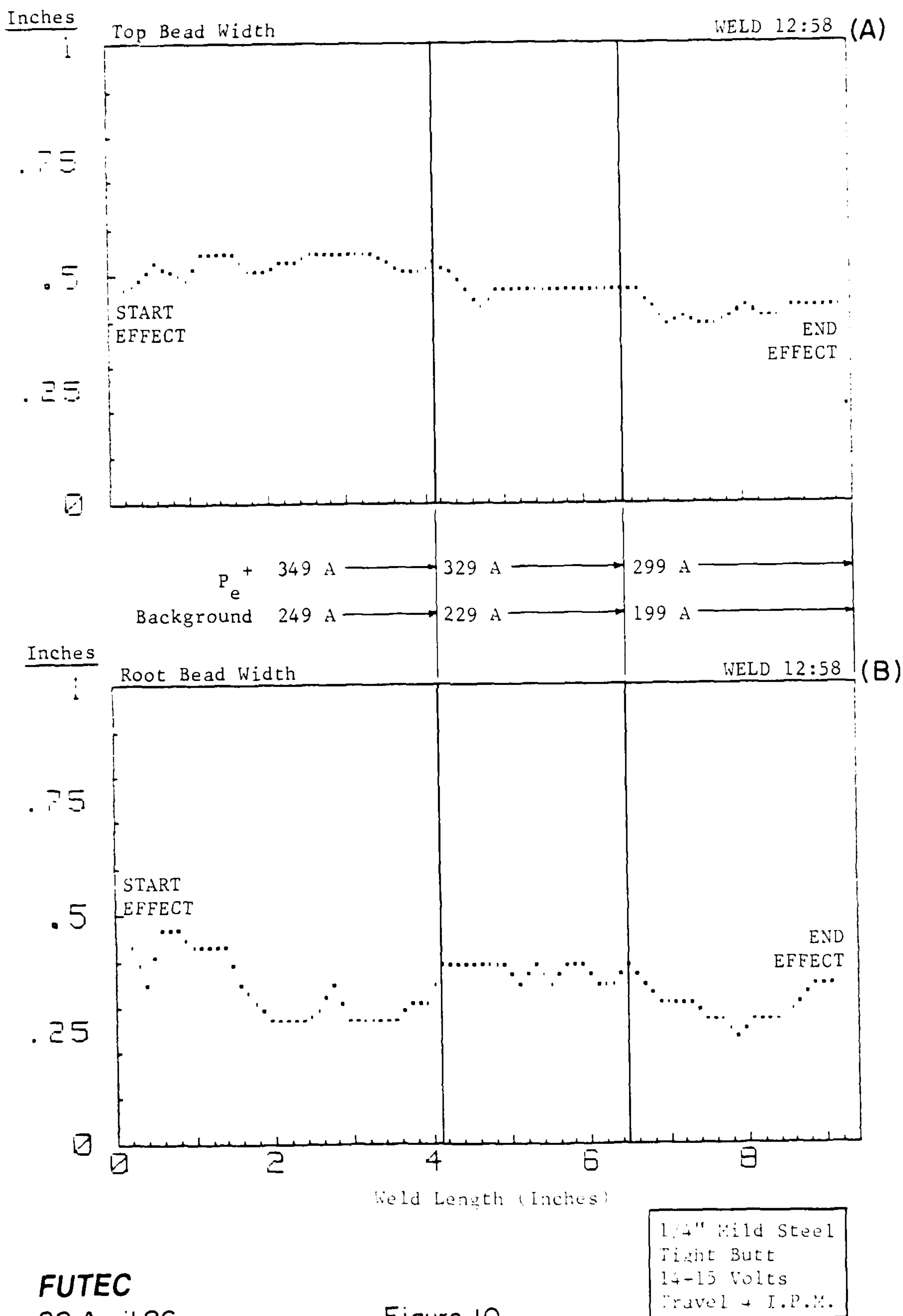

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Figure 10

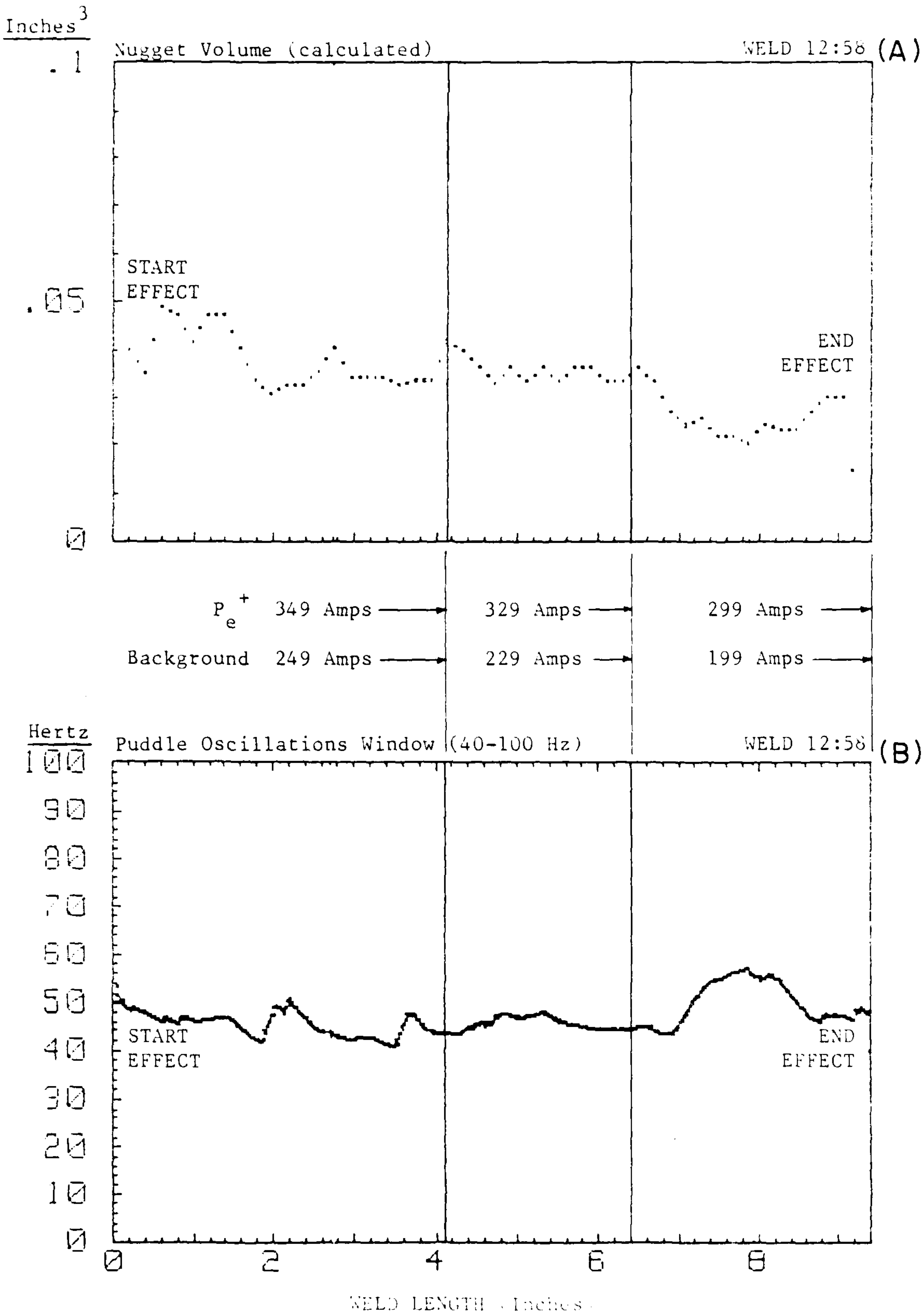

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Figure 11

2.3 **EDAP** SYSTEM DEVELOPMENT

The **EDAP** weld control scheme is one of multivariable estimation and control. The first requirement was to develop a computer controlled Data Acquisition, Reduction and Control system (**DARC**) which is interfaced to the welding equipment via a Special Purpose Interface (**SPI**). The basic approach is similar to that of Renwick and Richardson (Ref. 5), the technique of controlling weld size and penetration by estimating and controlling the Natural Frequency (f_N) of the weld puddle. However, our methods differ considerably. Also, a more sophisticated technique of frequency estimation is utilized to assure the technique is robust.

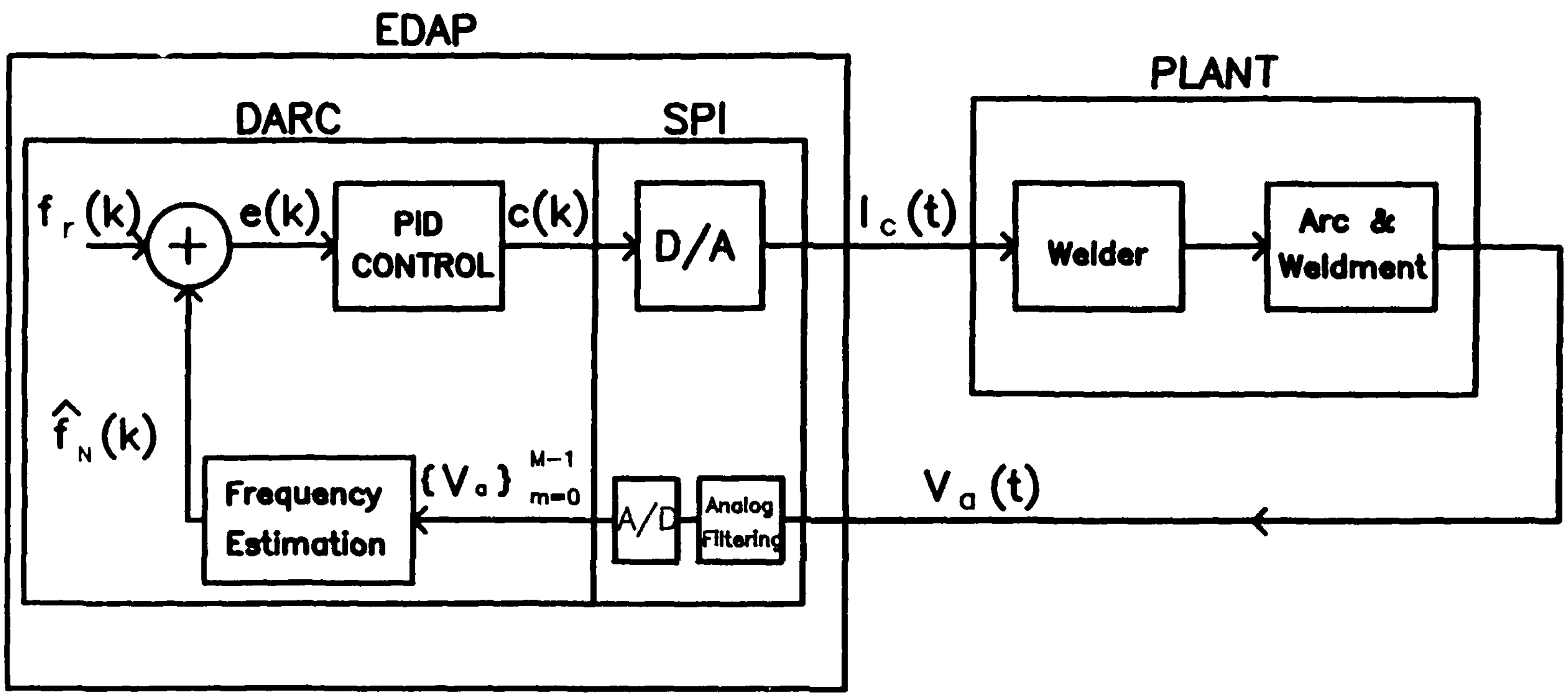
Final **EDAP** implementation, in its most complex form, may control as many as five weld parameters. They include current pulse amplitude, width, and repetition rate as well as average arc voltage, and BASE current. **EDAP** in its simplest form may control only BASE current. Primary efforts were concentrated on developing the acquisition methods and frequency estimation segments of the system, and experimenting with the variable welding parameter effects. This was to determine the range in which the controlled weld parameters have to be maintained.

The **EDAP** system, schematically illustrated in Figure 12, is comprised of two major sections. One is the computer controlled **DARC** section. Arc voltage signal acquisition, signal processing, weld puddle frequency estimation, and welder control are all handled by the **DARC** section which should be common to all **EDAP** systems.

The other section is the Special Purpose Interface (**SPI**) schematically illustrated in Figure 13, which initially handles analog filtering and analog digital conversion of the arc voltage and synchronization of the computer with the welding equipment. Then the **SPI** does digital to analog conversions of the current control signals, which are fed back to the welding power supply. Variations of the **SPI** section may be required for different types of welding equipment or other welding processes.

2.3.1 **EDAP** SYSTEM

The computer controlled **EDAP** system is described in terms of the hardware sections and associated software of the system. Together they implement data acquisition of the arc voltage and signal processing tasks, required both in the frequency estimation and the control algorithms.



EDAP
System Diagram

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Figure 12

2.3.2 **SPI** Section

The first requirement of the **SPI** section is interfacing the **DARC** section to the welding equipment, providing direct communication to the **DARC** computer. The purpose of the **SPI** is to capture the arc voltage signal, convert it to a form that can be operated on numerically for obtaining a frequency estimate of the oscillation of the weld pool, then finally implement a control law. Once a control signal is obtained this can be fed back to the welder.

The **SPI** section consists of analog arc voltage signal processing filters, analog to digital converters (ADC), and digital to analog converters (DAC). Analog filters are used to prepare for digital conversion of the arc voltage signal, which is measured directly between the tungsten electrode and the weldment. The differential amplifier circuit obtains arc voltage measurements, provides a ground reference and holds the arc voltage signal within the dynamic range of the A/D converters. An anti-aliasing filter is placed in line to eliminate high frequency signals which might corrupt the arc voltage signal upon digital conversion. A second order active lowpass filter with a -3 db cut off frequency of 117.0 Hz was used. Sampling rates for the analog to digital converters are computer controlled and are adjustable from 1 kHz to 10 kHz. The anti-aliasing filter provides approximately -15 db of attentuation at the lowest foldover frequency.

The **SPI** consists of a programmable clock, Analog to Digital Converters (ADC's) and Digital to Analog Converters. The **DARC** computer communicates to the **SPI** via the GPIO parallel interface. The ADC's are connected to the GPIO's input lines providing simultaneous reading of two analog voltages from the welding equipment. Similarly, the DAC's are driven, by the GPIO's output lines, also providing simultaneous output of two analog voltages. Selection of front panel control of the welder versus computer control is accomplished via a GPIO auxiliary control line. The GPIO's External Interrupt Request (EIR) line is used to synchronize computer data acquisition and reduction routines with the welder Milli-pulse timing. Figure 13 shows a block diagram of the SPI.

The ADC's incorporated in the **SPI** are used to monitor the arc voltage as a function of time. One reads the average arc voltage level while another is used to read the small signal changes in the arc voltage, caused by weld puddle oscillation. This second ADC receives its input from the anti-aliasing filter. This signal is

examined for the puddle oscillation frequency used in feedback control. The EIR line is used by the data acquisition software, as an interrupt to assure that data is taken at exactly the same time relative to the current Milli-pulse for all Milli-pulse rates and duty cycles.

Digital to Analog Converters are used to provide the welder with control signals for the BASE current level and excitation pulse level. DAC's have 8-bit resolution allowing 1 in 255 step control of welder current. This translates to 2.3 Amp current resolution on the present 600 Amp **POLY-PULSE** research welder. (Conversion times for the DAC's are much faster than the corresponding welding current settling time.)

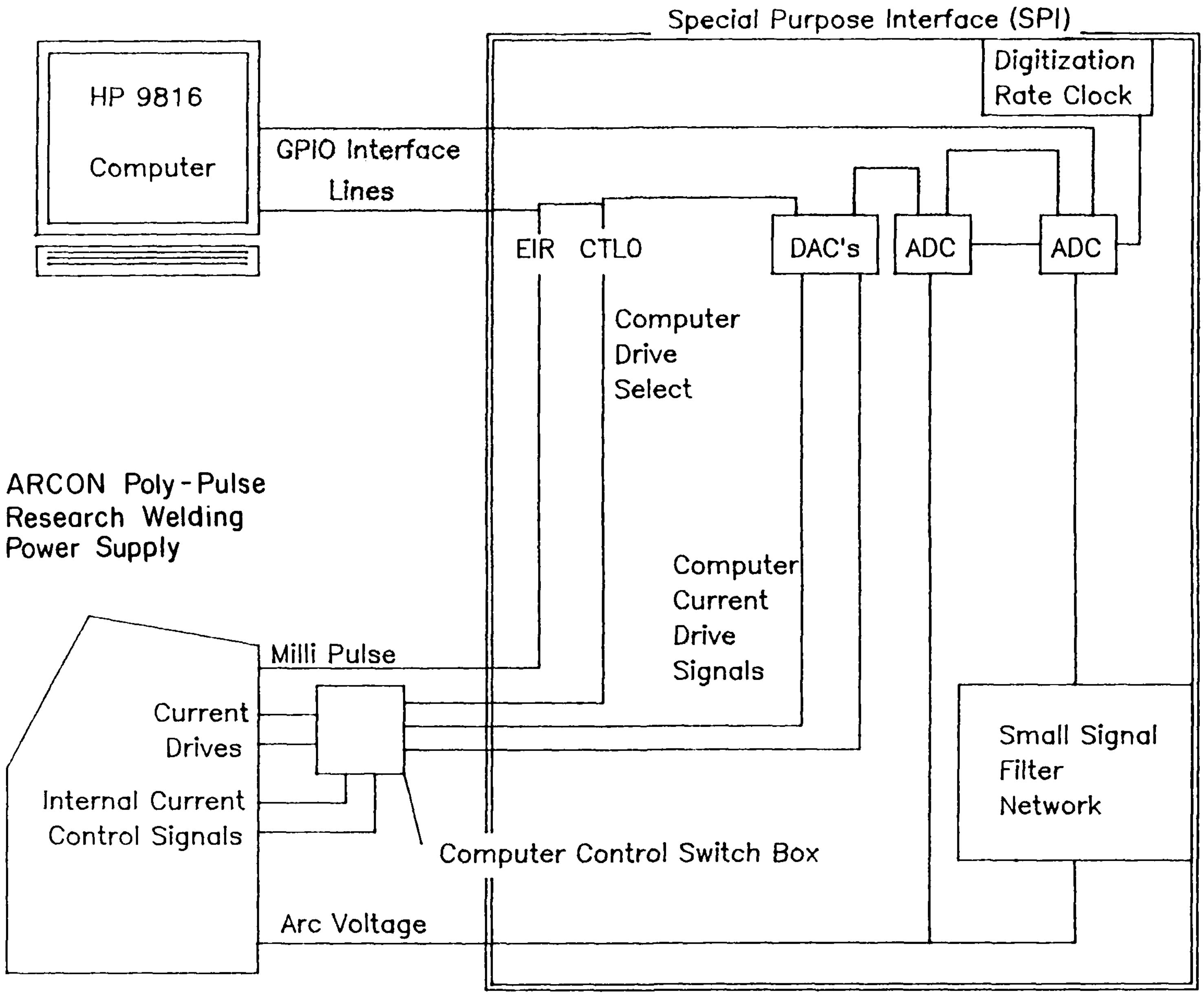

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Figure 13

2.3.3 **DARC** HARDWARE

In final product form, **EDAP** will rely on a simple microprocessor based system. However, since the major thrust of the **EDAP** research and development program is to determine the requirements to be placed on the **EDAP** system, the **DARC** research computer is by necessity more powerful and flexible.
The Hewlett Packard 9816 (see Appendix D) was selected for use in this project.

2.3.4 **DARC** SOFTWARE

Software developed in the course of **EDAP** research can be grouped in the following four categories:

A. Data acquisition software
B. Time Domain Data presentation software
C. Data reduction software
D. Welder control software

A. Data Acquisition Software

"Data acquisition software" consists of a program which captures arc voltage data from the A/D converters during a test weld, then stores that data on flexible discs. In these instances, the welder is typically under front panel operation as the controlled weld experiments are run. In these types of experiments, no active computer control of the welder is attempted nor are real time calculations performed with the weld data.

B. Time Domain Data Presentation Software

The next category of software is the "time domain data presentation software." As is often the case in computer controlled data acquisition systems, the DARC section gathers large amounts of data due to the length of the welds involved. Consequently, considerable work was done in designing a presentation method which meetings following criterian:

1. Data must be displayed in a consistent manner from weld to weld to allow meaningful comparison.

2. Data must be readily accessible for examination.

3. Software must be flexible enough to provide simple selection or modification of the data desired for study.

4. All outputs are identified as to source weld with their relationship to weld parameters.

The program developed was an interactive, graphics program allowing display of up to 50 records of data from any weld at one time. Also displayed is the time into the weld. Hard copies include all of these factors as well as a Record Number identifying the source weld. See Figure 4, page 22.

C. Data Reduction Software

The third type of software developed is termed "data reduction software" which primarily concerns the estimation of the weld pool oscillation frequency.

This very versatile software serves two purposes. The first task is for processing captured data for observation of the effects of varying any of the weld parameters than to provide information for aiding with the design of the welder control software. The second task is estimation of the frequency of oscillation that must be included in the welder control portion of the **EDAP** scheme. See Figure 5, page 26. Here, the sense of the data reduction is that the set of samples V_a is transformed in the estimation routine to a single point $f_N(k)$, representing the average frequency of oscillation for the time index k, indicating the k_{th} Milli-pulse low time samples.

The problem of estimating the frequency of the weld pool oscillation is complicated. Therefore, an estimation algorithm has several stringent requirements to meet. The first is fundamental to both purposes of the estimation routine and the last two are of primary concern in the automatic welding environment.

Therefore the algorithm:

1. Must correctly identify the frequency of oscillation of the weld pool from a signal which may be corrupted by noise from the arc plasma as well as quantization noise.

2. Must be stable. Meeting this requirement may require traps of the nature used by Renwick and Richardson (Ref. 5).

3. Must be computationally fast, requiring real time operation in an automatic control environment.

See Appendix F for complete details and algorithms.

D. Dynamic Welder Control Software (DWCS)

Welder control software that was developed, can be broken into two primary groups for the **EDAP** experimental system. The first of these is the actual BASE current control system which may eventually become the heart of the EDAP system. The second group is software that provides total control of the welder by computer, to simplify the experimental procedure of testing the background current control software. Based on the frequency estimate, provided by the estimator discussed in the previous section, a control signal is calculated and converted to analog form in the **SPI** then passed along to the welder to control the frequency of oscillation of the weld puddle, thereby controlling penetration and/or nugget size.

A proportional integral differential controller has been designed. See Appendix G.

A welding scenario has been computer simulated using a simple model for the puddle oscillation frequency. Here it is assumed that the Natural Frequency (f_N) of the puddle is inversely proportional to the average power of the welder at the arc. This is probably a crude approximation but is good to first order and was useful in determining estimates of the gains needed for the three control sections of the weld controller. The gains for the three sections were found through a trial and error process. The controller has not been placed in the EDAP research welding system due to time constraints.

A complete **EDAP** system has been given consideration. The final system will be designed as a Phase II project. See Appendix H.

3.0 EXTENDED RANGE VIDEO (ERV)

For the development of EDAP, the relationship of actual weld puddle movements to current pulsing needed to be observed in real time. Additionally, in order to completely study the events of weld puddle movements, without constant remaking of the same weld, video recording each weld was desirable. These research requirements could be accomplished by video recording. Additionally, actual visual records with precise synchronized relationships, could be video recorded by the use of split screen techniques. Various other electronic accessories provided time and measurement capabilities.

To accomplish these goals a research video system was put together. A high speed (300 pictures per second), high resolution camera was used which had multiplexing capabilities for projecting five sequential arc and puddle images on the screen at the same time. A second camera recorded the oscilloscope screen. By relating the movements in the welding puddle to both the current pulse wave forms and arc voltage changes, estimates of weld puddle oscillation frequencies and amplitudes could readily be made. See Figure 1, p.18.

3.1 RESEARCH USING ERV

The effects of adjustments of the welding and pulsing parameters could be observed in real time. This capability saved a large number of research hours and material expenses. This was accomplished primarily by observing the oscilloscope on the video CRT screen while adjustments were made as welding progressed. Changes in the shape, amplitude and frequency of the arc voltage wave forms were obvious in their controllability. The capability of readily being able to control the wave forms' amplitude and frequencies, and clearly observing variations, assured that:

1. **Movements in the weld puddle were real and could be related to parameter changes.**

2. **The weld puddle movements are very distinguishable, measurable, and therefore can be used for control purposes.**

One of the major discoveries made during this research was the result of being able to go back and review the video tapes of previously made welds:

1. **Replaying of tapes at high speeds showed the existence of a "traveling wave."**

2. **Changes in welding parameters would modify the traveling wave or eliminate it.**

Video tapes were eventually used to confirm the wave form plots and frequency estimates produced by the research computer.

Differences were observed and the computer frequency estimation techniques were modified. Additionally, the analog filtering was changed to provide more accurate wave form plots.

3.2 ERV EQUIPMENT

The ERV system was not completely developed. Equipment operating problems and insufficiencies, most uncorrected by the original manufacturer, were a great hindrance. Additionally, the strobe system was never capable of accomplishing the task represented. A new lighting system was investigated and partially designed but abandoned because of time constraints and budget limitations.

The various accessories used with the ERV system are commented on as follows:

1. Screen Splitter - Excellent.
   Provided the ability of two cameras to be shown on the CRT simultaneously. Provided accurate comparison of cause and effects.

2. Time Generator - Excellent.
   Provided an accurate record of the events throughout each weld.

3. Contour Synthesizer - Excellent.
   Provided the capability of emphasizing the smallest details of the weld puddle, including waves in the puddle.

4. Cross Line Generator - Of better value might be a superimposed grid which would provide more precise measurements in two planes.

5. High Speed Strobe - Poor. - Insufficient light.

6. The final 3/4" high resolution recorder (VTR) was much better than the original recorder which was not high resolution. Master tapes of important welds are retained on these cassettes.

7. A 1/2" recorder VCR was used to record most of the welds for economical historical purposes and for eventual editing. (This recorder is not high resolution and skips every other picture on playback.)

Tapes for the large number of welds made for this research still exist. This means that, as in Phase I, previously made welds can be reexamined and related to the parameters used. Because the continuous wave forms which indirectly demonstrate the movements in the puddle, can be reexamined and related to the work sheet records, and computer printouts, a good amount of research can be continued without repeating welds.

4.0 PULSE WELDING

4.1 PULSED ARC RESEARCH, GTAW A710 STEEL

Much has been published regarding the many benefits of pulse welding. The subject is very broad and lacks definition. This portion of the research effort is for square wave pulse welding at rates generally higher than the maximum 10 Hz levels typically used for heat control only.

The Arcon POLY-PULSE welding power supply has the capability of pulsing at MILLI-PULSE rates to 999 Hz, MICRO-PULSE rates to 50 K Hz, and can superimpose one on the other. See Appendix E.

Some of the generally expected results from pulsed welding which were observed were:

A. Stiffer arcs which are less subject to arc blow generally produce narrower beads and deeper penetration.
B. Refined grain structures are produced and are the result of even cooling of the entire weld puddle.
C. Lower heat input due to the lower required currents and more efficient arcs.
D. Lower porosity because of induced convection in the puddle which sweeps gas bubbles to the surface.
E. Homogeneous structure due to vibration and the induced convection in the liquid metal, particularly at the fusion boundary.

These benefits of pulse welding should be of particular benefit for HSLA steels both for weld quality and physical properties.

Preliminary tests were made to find the average current level that would produce the largest weld without fully penetrating the plate. This was done so that the welds were not affected by variations in root bead widths or possible diaphram effects of an unsupported weld. The same fixture was used for **EDAP** development wherein a conforming copper back-up bar was pneumatically pressed against the back of the joint. The back-up bar groove is 1/16" deep by 1/2" wide. Once the average current levels were established, all welding for each pulse type was completed at the established average currents.

4.2 GENERAL TEST RESULTS Figure 14

All welds at all pulse rates exhibited grain refinement to some degree. The top surfaces of the welds showed the most refinement which should be of value in any cyclic type of stress. Dendrites were broken up as compared to the large columnar dendrites formed in steady D.C. welds. Iris type patterns were seen in all pulsed weld nuggets. Observed in all welds was an Fe+Cu precipitate which appeared to be broken up by the pulsed arc. Some random porosity was seen in the steady D.C. welds. The base metal contained a considerable amount of porosity. <u>No</u> porosity was observed in any of the pulsed welds.

MACRO STRUCTURE 60:48A

7.5X 5% Nital

MICRO STRUCTURE 60:48A

50X 5% Nital

MILLI-PULSE (50 Hz)
A710 Steel 3/8" Tight Butt
Peak 325 Amps 10 mS
Background 225 Amps 10 mS
14V...........4 IPM

WELD NUGGET No Porosity
Refined Grains

MICRO STRUCTURE 61:25E

CONTROL WELD **STEADY DC**

A710 Steel
3/8" Tight Butt
300A @ 14V
4 IPM

Large columnar grains
Heavy base metal porosity
Random weld porosity

Fusion Line

50X 5% Nital

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Figure 14

All of the following welds made in this section were completed on A710 steel, 3/8" thick using end tacked tight butt joints. Cleaning was by sanding and wiping with acetone.

4.3 MILLI-PULSE (1-999 Hz) Figure 15A

There are four controls for MILLI-PULSE on the ARCON POLY-PULSE welding power supply:

A. HIGH CURRENT - 1-600 Amps
TIME - 1.0-999.9 ms (width)

B. BASE CURRENT - 1-400 Amps
TIME - 1.0-999.9 ms (width)

All MILLI-PULSE welds were run at equal HIGH and BASE current times (50% Duty Cycle).

All MILLI-PULSE welds resulted in deeper penetration than the steady D.C. control welds. Penetration gradually decreases with increasing pulse rates.

4.4 MICRO-PULSE (1 K Hz - 50 K Hz) Figure 15B

There are five controls for MICRO-PULSE on the ARCON POLY-PULSE welding power supply:

A. HIGH CURRENT - 1-600 Amps
TIME - 1-999 us (width) Set with BASE current.

B. INTERMEDIATE CURRENT - 1-600 Amps
TIME - 1-500 us (width)

C. BASE CURRENT - 1-400 Amps
TIME - 1-999 us (width) set with HIGH current.

All MICRO-PULSE welds resulted in deeper penetration than steady D.C. control welds. Penetration gradually increases with increasing pulse rates.

4.5 POLY-PULSE (MICRO-PULSE superimposed on MILLI-PULSE) Figure 16

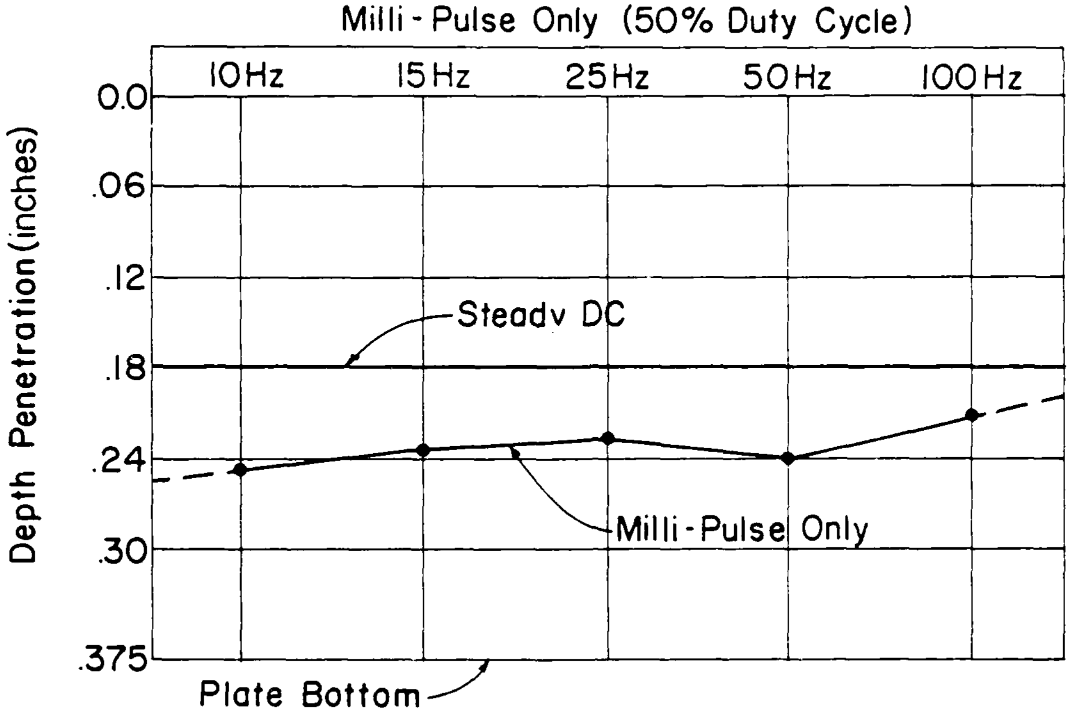
Penetration amounts for POLY-PULSE welds varied greatly according to the specific combinations of MILLI-PULSE and MICRO-PULSE.

The graphs show penetration patterns that are obvious and must be considered in selecting parameters for either maximum penetration or maximum width. For example, the maximum penetration conditions are obtained at 50 Hz MILLI-PULSE combined with 7.5 K Hz to 15 K Hz MICRO-PULSE.

PULSE RATE VS PENETRATION

Milli-Pulse Only
Micro-Pulse Only

(A)



(B)

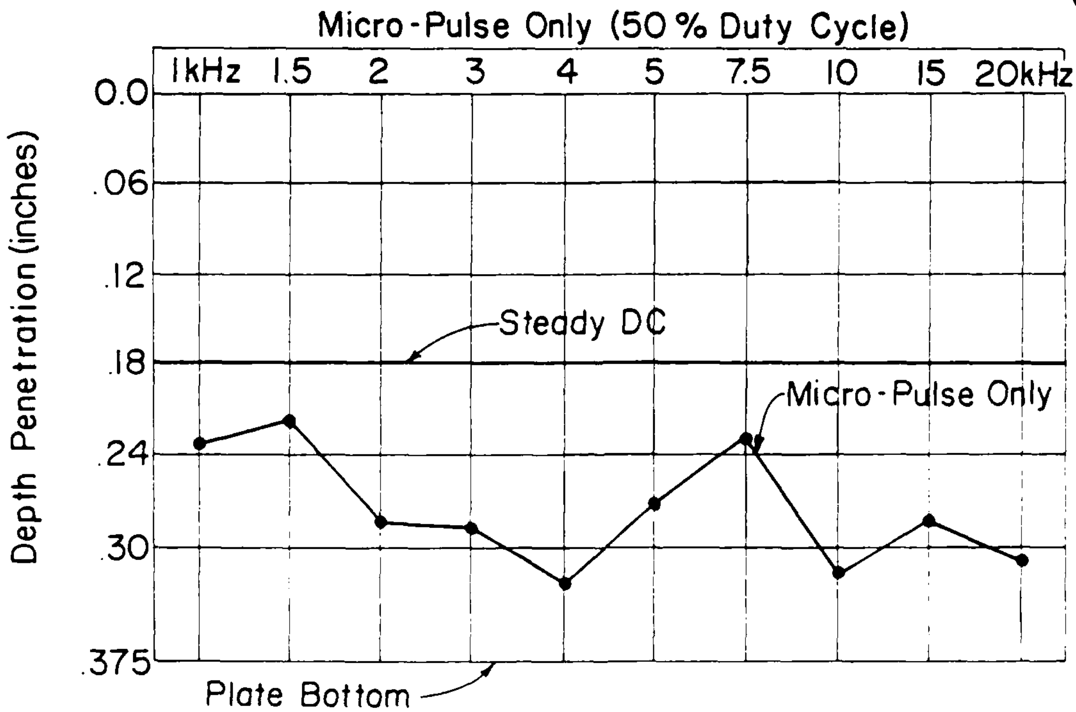


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Figure 15

POLY-PULSE Weld Penetration
Various Poly-Pulse Rates as
Compared to Steady DC and Milli-Pulse Only

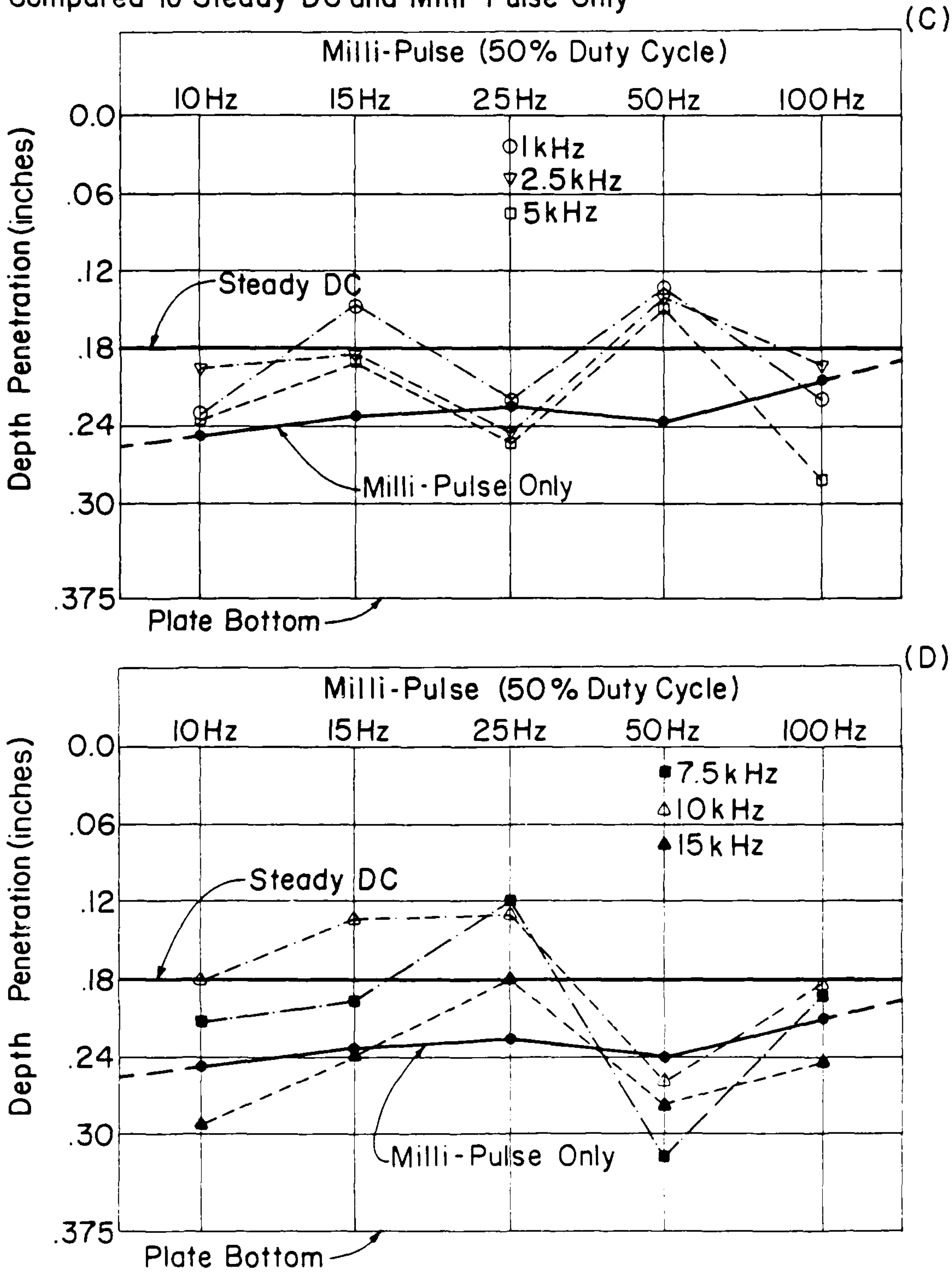

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Figure 16

4.6 PULSE WELDING CONSIDERATIONS

Comparing the curves (Figure 16) for pulse welding, the patterns that occur do not appear to be straight line occurrences except for the MILLI-PULSE welds. One should also be cautious, even with the MILLI-PULSE welds, of extending the connecting lines beyond the actual test points.

The POLY-PULSE welds have patterns that suggest certain combined pulse rates are additive, increasing weld penetration and decreasing width. Other combined pulse rates are additive, but in a direction that decreases penetration and increases bead width.

Further inspection of the weld samples leads to what may be an **important discovery for nugget geometries resulting from POLY-PULSE welds.** A considerable number of studies have been published regarding convection flow patterns in weld puddles. Two types are generally described: Puddles with center outward flows producing shallow wide nuggets and puddles with inward flows producing relatively narrow, deep penetrating nuggets. **A third type of nugget has been identified in our research for pulsed welding. This nugget form is being termed a "Transition" weld or nugget.** See Figure 17.

During test welding, curious movements of the arc were observed causing the weld beads to move irregularly from side to side under the electrode. This occurs particularly at high currents, perhaps over 250 Amps average. When these welds were cross-sectioned and etched, the nugget shapes were irregular, usually characterized by being off the center line of the weld joint. The top surface is usually uneven, one side of the nugget resembling an outward flow condition, with the other inward flow condition.

4.7 PULSED WELDS Tables 2, 3, 4

A group of pulse welds were charted with measured depths, widths, areas and nugget shapes according to what is believed to be the convection flow patterns. A study of these dimensions will show a correlation to nugget shape and type.

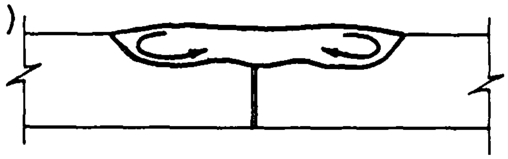
POLY-PULSE welds, outlined with broken lines in Table 4, are selected groups of welds, that should result in stable weld puddles with predictable bead shapes. Most of the welds outside these lines may be unpredictable and are designated "Transition" welds.

WELD NUGGET SHAPES

Change due to convection flows in pulsed arc GTAW welds caused by changes in pulse rates.

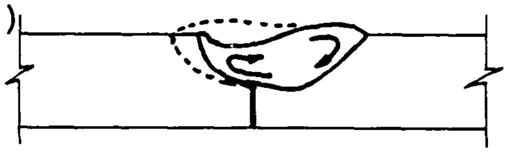
A710 Steel

(A)



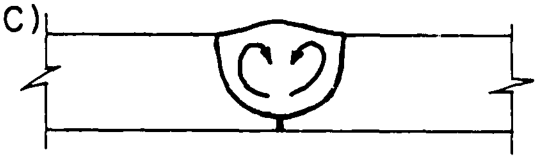
STABLE
Very Smooth Top Bead
(Centered)

(B)



UNSTABLE
Irregular Top Bead
(Not Centered)

(C)



STABLE
Even Top Bead
(Centered)

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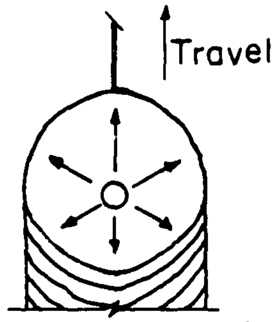
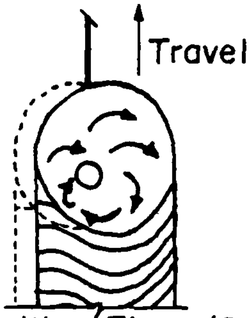
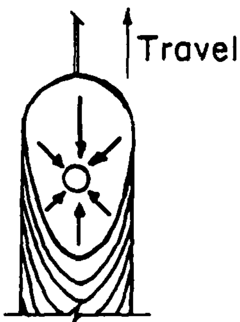
Magnetic arc control, arc deflected to advanced position.



Outward Flow (C↗)



Transition Flows (C↗↙)



Inward Flow (C↙)

2% Thoriated Tungsten Electrodes
1/8", 5/32", 3/16" Diameters
30°-90° Vertex Angles
.035-.050 Truncation
1.5-4.5 I.P.M. Travel Speed
Argon, Helium and Helium+Argon

Figure 17

PULSE WELDING CONDITIONS for Tables 2 and 3

Base Material - A710 Steel 3/8" thick
Joint - Tight Butt
Temperature - Plates 65°-67°F (no preheat)

MODE	VOLTS	CURRENT (Amps) 50% Duty Cycle			
		HIGH	INTERMEDIATE	BACKGROUND	**AVERAGE** Calculated
STEADY D.C. (Control Weld)	14	300	---	---	**300**
MILLI-PULSE	14	325	---	225	**275**
MICRO-PULSE	14	290	---	190	**240**
POLY-PULSE	13	380	330	280	**330**

Gases: He 30 CFH and Ar 15 CFH, 3/4" ID cup.
Travel: 4 I.P.M., 5 second start delay.
Electrode: 2% thoriated, 5/32" dia.
30° vertex, .050" truncation.
3/4" extension from edge of cup.
All welds at same apparent arc length.
Magnetic Arc Stabilizer to preposition arc.

NOTE:
ALL WELDS WERE MADE AT CURRENT LEVELS THAT ASSURED:

1. FULL PENETRATION WAS NOT ACHIEVED AT ANY OF THE PULSE FREQUENCIES TESTED

2. PENETRATION AMOUNTS WERE SIMILAR TO THE STEADY DC CONTROL WELDS.

FUTEC Table 2

MILLI-PULSE ONLY
MICRO-PULSE ONLY

WELD NUGGET SIZE AND TYPE

MILLI-PULSE ONLY	DEPTH	WIDTH	AREA*	SHAPE**
10 Hz	.282 in.	.427 in.	$.35\ in.^2$	C/
15	.268	.445	.35	C/
25	.228	.515	.35	C/
50	.262	.462	.35	C/
75	.272	.462	.35	C/
100	.227	.478		C//
200	.250	.405	.32	C/
400	.249	.416	.32	C/
500	.240	.427	.32	C/
MICRO-PULSE ONLY				
1.0 K Hz	.233	.478		C//
1.5	.218	.480		C//
2.0	.284	.483	.37	C/
2.5	.288	.435	.35	C/
3.0	.288	.391	.34	C/
4.0	.325	.450	.38	C/
5.0	.271	.424	.34	C/
7.5	.226	.459	.32	C/
10.0	.316	.405	.36	C/
15.0	.284	.392	.33	C/
20.0	.309	.381	.34	C/
STEADY DC (Control Weld)	.180	.720	.36	C/

* Area – $\frac{A}{\sqrt{W \times D}}$

** Shape Nugget (convection flow)
- C/ Outward Flow, **Stable**
- C// Transition Flow, **Unstable**
- C/ Inward Flow, **Stable**

FUTEC Table 3

POLY-PULSE - Weld Nugget Size and Type

MICRO-PULSE \ MILLI-PULSE	*	10 Hz	15 Hz	25 Hz	50 Hz	100 Hz
1 K Hz	**D**	.232	.148	.222	.134	.220
	W	.598	.725	.680	.784	.696
	A		.33		.33	.39
	S	C↗↙	C↗	C↗↙	C↗	C↗
2.5 K Hz	**D**	.197	.186	.245	.141	.195
	W	.595	.595	.647	.756	.628
	A				.33.	.35
	S	C↗↙	C↙↗	C↙↗	C↗	C↗
5.0 K Hz	**D**	.233	.190	.253	.148	.284
	W	.536	.671	.525	.728	.621
	A	.35			.33	
	S	C↙	C↗↙	C↙↗	C↗	C↗↙
7.5 K Hz	**D**	.213	.197	.120	.317	.191
	W	.596	.708	.794	.553	.655
	A		.37	.31	.43	
	S	C↗↙	C↗	C↗	C↙	C↗↙
10 K Hz	**D**	.182	.132	.130	.260	.184
	W	.592	.765	.830	.606	.688
	A			.33	.40	
	S	C↗↙	C↙↗	C↗	C↙	C↗↙
15 K Hz	**D**	.293	.239	.180	.277	.243
	W	.645	.574	.722	.568	.580
	A		.36	.36	.40	
	S	C↗↙	C↗	C↗	C↙	C↗↙
STEADY DC (Control Weld)	**D**	.180	.180	.180	.180	.180
	W	.720	.720	.720	.720	.720
	A	.36	.36	.36	.36	.36
	S	C↗	C↗	C↗	C↗	C↗

* D - Depth (inches) W - Width (inches) A - Area $\frac{A}{\sqrt{W \times D}}$	S - Shape Nugget (Convection) - C↗ Outward Flow, **Stable** - C↗↙ Transition Flow, **Unstable** - C↙ Inward Flow, **Stable**

FUTEC TABLE 4

4.8 ANALYSIS TRANSITION WELDS

This "Transition" effect may only occur in welds in which vibration is induced. (No attempt was made to make steady D.C. welds to check this because of time restrictions.) These vibrations no doubt can be induced by magnetic stirring, mechanical impacts, or arc pulsing. Brown, et al (Ref. 15), states the following:

> "Vibrations also have a definite effect on the bead shape of welds; the controlling parameters are waveform, amplitude, and frequency. The most important parameter is waveform. It was found that with impact vibrations, if the direction of impact was from beneath the weld, root reinforcement increased, and the bead became flatter compared to normal welds. Sawtooth vibrations, with the higher velocity down, caused a net force up and the puddle could be made to 'crown,'.... With sinusoidal vibrations, no effect was observed until the vibration amplitude became sufficiently great to cause drops of weld metal to be expelled from the weld pool. In this case, the bead surface merely became rough."

As previously indicated in 2.2.1, C.3, joints and their configurations affect penetration and weld bead width, made at the same welding parameters. The potential for joint designs modifying flow patterns in the molten weld pool also exists. It suggests that there might be attenuation of the pulse frequencies, if any type of a joint is used, including tight butts which may also have oxide layers, which could worsen the condition even further. This can be much like what occurs with ultrasonic inspection, as air is a strong attenuator, explaining the reduced penetration amounts where a gap exists. The engineer or technician must find a usable range of pulse welding parameters that avoid the "Transition" type weld beads.

5.0 DATA BASE A710 STEEL

5.1 At the time this research program was proposed it was expected that all necessary data would be developed for pulse welding 3/8" thick A710 steel. It was also believed that this data could be extrapolated to include other HSLA steels in nearly the same thicknesses. The GTAW process exhibited some problems for welding the specific analysis of A710 used in this research. Other discoveries, including unusual effects that different pulse rates have on welding this steel, compounded the problems of developing a simple data base.

Sections 2.0 **EDAP DEVELOPMENT** and 43.0 **PULSE WELDING** describe most of the difficulties leading to the final decision to continue research on thinner mild steel plates. The two major problems were: first, the very wide beads and second, the difficulty in consistently obtaining full penetration. These difficulties may be related.

5.2 INITIAL RESEARCH

Level I Research reasonably indicated that varying the basic welding conditions would not overcome the problems of Pulsed GTA welding of 3/8" thick A710 steel. These included:

A. Current levels.

B. Travel speeds.

C. Gas mixes.

D. Joint gaps and design.

E. Cleaning.

F. Electrode size and shape.

The following paragraphs detail these welding conditions with the results combined from both Level I and Level II Research.

A. CURRENT

The very large and wide beads produced at current levels of over 400 Amps were considered metallurgically unacceptable. These large sized puddles usually promote grain growth and definitely have unacceptable amounts of heat input. Even at average current levels of over 400 Amps, depth penetration was inconsistent. This problem may partially be related to the nature of the GTAW process as detailed by Chihoski (Ref. 8).

Currents to 600 Amps were tested, all resulting in unacceptable welds.

B. TRAVEL SPEEDS

Faster travel speeds provide much more acceptable bead shapes, particularly at 6-10 I.P.M. There were two disadvantages to these higher speeds:

1. Full penetration could not be consistently achieved in 3/8" plate.

2. The **EDAP** research required full penetration welds to be successful.

A weld speed of 2 I.P.M. was settled upon for the initial research. This limit was selected to minimize front wall effect. Later when the magnetic arc positioner was used speeds were increased to 4 I.P.M.

C. GAS MIXES

Gas had a limited effect on reducing the large puddle size.

D. JOINT GAPS

Only by reducing the thickness of the plates by machining, could acceptable weld shapes be produced. Various joint geometries and gaps also had arc blow problems. Machining all of the remaining plates was considered impractical.

E. CLEANING

The A710 plates as supplied from the mill had very heavy scale. Welds had very poor finishes unless all of the slag was removed by grinding. Unground plates resulted in uneven beads.

F. ELECTRODE SIZE AND SHAPE

An enormous amount of effort went into determining the ideal electrode size and shape that would provide maximum penetration, best response for **EDAP**, and not deteriorate rapidly. Electrode shapes were tested based on the original work by Savage et al (Ref. 16) and continuing works by Chihoski (Ref. 8) and most recently Keys (Ref. 9) without much success.

By continued investigation the 1968 paper by Ando, et al at Osaka University (Ref. 17) was found. This paper takes into consideration travel speeds, at high currents, in thick plate sections. New curves were developed for their charts for 4 I.P.M. See Figure 18.

Based on this chart, weld testing confirmed that a 30° vertex angle, using a .050" truncation provided maximum penetration, good bead shape, excellent responses for **EDAP**, with acceptable electrode life. All final welding was done with this configuration.

Originally 3/16" diameter electrodes were used because of the high current levels employed in attempts to get full penetration welds in 3/8" A710 plate. Finally, all research welding was done using 5/32" diameter electrodes which gave the most satisfactory bead shape and maximum penetration.

A 3/4" electrode extension from the bottom of the #10 cup was used. This provided excellent viewing and good gas coverage. A newly ground electrode was used for every final test weld.

As a general observation it was noticed the specific vertex angle had less effect at high speeds of perhaps over 8 I.P.M. There unfortunately appears to be a transition area of 2-8 I.P.M. which are the speeds most common to this type of welding.

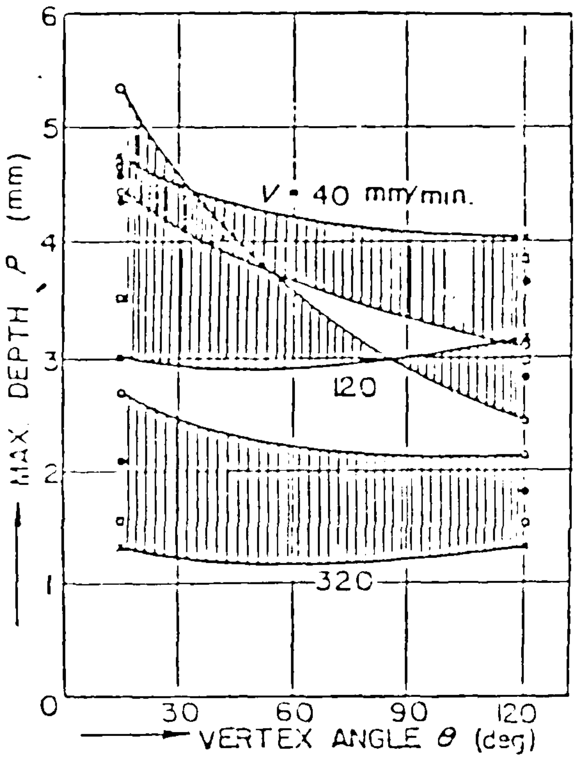
Electrodes having vertex angles of 30°- 45° had very stable arcs. Electrodes having vertex angles of 105° - 120° had unstable arcs. Some arc wander was experienced at 60° - 90°. This also appears to agree with the Ando, et al data.

(Again, as currents were increased arc wander increased. This is believed to be a characteristic of welding A710 steel.)

An example of the relationship of travel speed and vertex angle to penetration was that the <u>same depth of penetration resulted at 1.6 I.P.M. as that at 4.7 I.P.M.</u> using a 30° vertex angle (320 Amps 1/8" dia.).

TUNSTEN ELECTRODE TIP SHAPE

Osaka University (Ref. 17)



Bead width and penetration depth vs. vertex angle of cathode when travel speed is varied.

Interpolation at Weld Speeds 4 I.P.M.

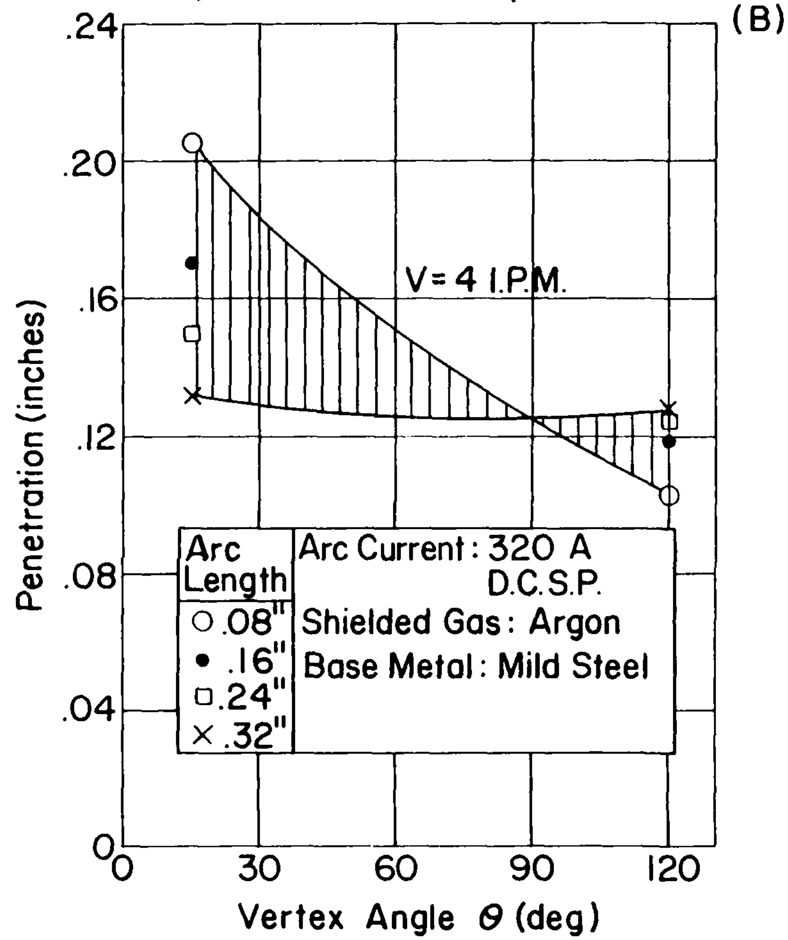


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Figure 18

5.3 GTA WELD A710

The difficult problems encountered when welding 3/8" thick A710 steel may possibly be related to the specific chemical analysis of the plates purchased. (See Appendix A) It is well known that alloys in the steel will cause changes in puddle shape:

- High silicon contents usually increase bead width.
- High manganese contents can cause arc wander.
- Increasing aluminum may increase depth of penetration.

Additionally, much has been written on the effect of "minor alloying constituents" and weld puddle shape, as shown by Heiple and Roper (Ref. 18). Even though alloying appears to change convection patterns in the liquid weld puddle, pulse welding can change these same patterns. Refer to section 4.0. Perhaps pulse welding can fully control these patterns regardless of the "minor alloying constituents."

Finally, the physical properties of the A710 base metal may also be adversely affected by the initial large welds made at high heat inputs. Therefore, the GTAW process at this time should be limited to average currents under 400 Amps. This reduces the possibility of full penetration welding 3/8" thick A710 in a single pass. Tight butt joints 1/4" thick on A710 steel, can be completed with reasonable control and acceptable bead shapes with full penetration.

5.4 FILLER WIRE

A close matching filler wire was never located for A710 plate. The specially drawn down SAW wire appears reasonably close (See Appendix B). This reinforces A. Pollack's recent comment at the Atlanta meeting that "There is a major problem in the United States ......Steel is outrunning the consumables," and further, "The wires that meet all of the requirements are foreign." Again, filler wire additions were never used during this Phase I research.

6.0 CONCLUSIONS

6.1 EDAP - ELECTRO DYNAMIC ARC AND PUDDLE CONTROL

Successful Level I research work led to the high confidence level that encouraged further development of precise methods for determining weld puddle oscillation frequencies. Level II research completes the feasability portion of Phase I with very encouraging results.

6.1.1 PROCESS VARIABLES

A. A 1 ms to 3 ms square wave current pulse (P_e^+) will excite the weld puddle into fundamental oscillation. Longer pulse widths may dampen puddle oscillations.

B. Amplitude of the excitation pulse (P_e^+) of 70-90 Amps (IP_e) above 250-350 Amp BASE current, will do a strong job of causing puddle oscillations. Pulse amplitudes of 100 Amps or more causes a "Traveling Wave" effect. Pulse amplitudes less than 60 Amps are unreliable in developing puddle oscillations.

C. Travel speed is limited to approximately 4 I.P.M. for full penetration welds on 1/4" steel plate. This speed does require using a magnetic arc positioner (MAPS) for deflecting the arc forward to avoid "front wall effects." This speed, 4 I.P.M., may also be a limit for accurate sensing of puddle oscillations.

D. Size of the puddle may reach a maximum for which reliable puddle oscillations and/or usable small signal voltage variations exist. This may be at approximately 350-400 Amps average current, traveling at 2-4 I.P.M. on steel.

E. Very high gas flows of over 80 CFH with a #10 cup, may interefere with the fundamental oscillation of the weld puddle.

F. Both Argon and Helium gases, including mixes of these gases, were capable of providing good small signal voltage response at the 250-550 Amp levels.

G. Electrode tip shape does not appear to be critical for sensing puddle oscillations at high average current levels (250-550 Amps).

H. Arc length is not critical to the **EDAP** system sensing capabilities at the high current levels (250-550 Amps) tested. Short arc lengths of 13 Volts are impractical because of contamination with the weld puddle. Longer arc length of over 18 Volts are not desirable from an efficiency standpoint and also limits penetration. The

normally employed arc length of 13-16 Volts provides good small signal voltage response.

6.1.2 GENERAL OBSERVATIONS

A. The **EDAP** system clearly demonstrates the close correlation between weld puddle Natural Frequencies (f_N) to nugget size and root width of a fully penetrated weld.

B. A discernable step (increase) in both voltage level and amplitude is seen when full penetration occurs in an unsupported weld. Amplitude and voltage rapidly increase just prior to full penetration and therefore may possibly be used to predict burn through. The increase in amplitude occurs at approximately the same frequency level as the same size weld in a partially penetrated weld.

C. Very large weld puddles, at this time, may present enough difficulties that research above the 400 Amp average current level forces the development of a control system that may be impractical and extremely expensive. Some of the limitations of the GTAW process may be contributing to the very large puddle problems wherein a penetration plateau may exist between 275 and 450 Amps for steels.

For metallurgical reasons very large puddles should be avoided as they tend to promote grain growth.

Puddles produced in the 250-350 Amp levels at 4 I.P.M. travel speeds, do not exhibit the problems of the very large puddles and have some advantages over the very small puddles produced by previous researchers. Weld puddles developed in these moderate current ranges are not sensitive to very short term events. Also, the design and implementation of a control is simplified as there is more time for frequency calculations and the development of control signals.

D. There are many known welding and metallurgical advantages to MICRO-PULSING the arc. MICRO-PULSING appears to aid in quieting the surface of the weld puddle, eliminating secondary wave forms. Superimposing of MICRO-PULSE on the BASE current level has the potential for not only improving welding but aiding in the implementation of **EDAP**.

E. The possibility of inverting of the excitation pulse (P_e^-) was discovered near the end of this research. Instead of applying a short duration pulse (P_e^+) on a low BASE current level, the scheme is reversed with a short duration drop in current from the BASE level (P_e^-).

A limited series of test welds indicates that this may be a more stable technique for sustaining fundamental puddle oscillations. This new method appears to be less sensitive to process variables and functions at higher travel speeds. (All reported data and most opinions in this final report on **EDAP** are based on the increasing (P_e^+) excitation pulse method.)

The data acquisition system used for **EDAP** was not designed to take data in this inverted scenario so no oscillation frequency data could be obtained for the single weld made using this excitation scheme. The arc voltage was monitored on an oscilloscope during the run and the puddle oscillation appeared more stable when compared to the welds run under the normal pulsing scheme. This technique appears to offer great promise for obtaining better oscillation frequency estimates. The DARC subsystem of **EDAP** can readily be modified to handle both pulsing schemes.

6.1.3 APPLICATION CONSIDERATIONS

A. Some of the results of testing the **EDAP** system have been presented in the observation mode. The information is available in several different frequency ranges *inferring* that the puddle may have more than one natural frequency. This may be similar to effects found in different types of resonant cavities. Most cavities will oscillate at a large number of frequencies. Examples of these include a drum, a microwave wave guide and numerous others. This makes it possible to capture not only large variations in weld size but also to observe relatively small changes.

Final **EDAP** implementation may exploit these factors and monitor a set of frequency bands to add some redundancy to the calculations. There is a probability that different frequency ranges, along with amplitude changes, will be used to control different welding parameters.

B. Earlier research efforts by MIT and OSU were accomplished using steel, stainless steel, and nickel base alloys. Fundamental oscillations of the weld puddle were confirmed for these base metals. FUTEC's efforts were primarily with HSLA steel A710, and mild steel. The difficulties for welding A710 were believed to be welding problems only. **EDAP** testing worked equally as well with A710 as with mild steel. Brief tests for welding aluminum also indicate Natural Frequencies (f_N) of the weld puddle can be observed. This leads to the probability that most weldable metals exhibit fundamental puddle oscillations based on size and they are candidates for the **EDAP** control system.

C. Excitation pulse repetition rates, should be as fast as possible for many reasons:

1. Fast rates assure that estimates of puddle frequencies are more continuous and therefore more reliable. Those puddle oscillations directly following the excitation pulse (P_e) are very strong and resist contamination by external influences.

2. Travel speeds will be increased, due to the continued development and improvements in the **EDAP** system, for both thin and thick base metals. Slow pulse rates may cause inconsistent puddle geometries, seriously limit travel speeds. Slow pulse rates may also cause heating and cooling of the puddle interfering with the relationship of the preset control frequencies and actual puddle size.

3. In all probability the first consideration in using the **EDAP** system will be travel speed. Travel speed will need to be selected and then maintained for the entire weld. For full penetration welds on thick sections, this will probably be the fastest speed at which the front wall will not cause electrode contamination. For thinner welds this probably will be the fastest speed at which a good signal can be obtained from the oscillating weld puddle.

4. At a given current level, weld bead size will change with speed. Faster speeds will produce narrower weld beads and no doubt higher frequencies from the puddle surface. With a fixed travel speed the preset control frequency will more accurately indicate actual nugget size.

Continued progress during **EDAP** research encouraged continued development of the **EDAP** system. Level I research clearly demonstrated the feasability of the concept. Successful Level I experiments led to the Level II research where it was established that an electronic system could produce meaningful and therefore usable control data. This second step moved the research from the basic feasability level, to the realm of proven system capabilities, which should lead to completion of a practical control system.

6.2 ERV - EXTENDED RANGE VIDEO

The research video system was valuable in doing the types of welding research undertaken. The most valuable part of this remains in our ability to go back and continually study welds previously made. These video records provide a method for accurate comparison to any future welds made.

The speed of the video camera of 300 pictures per second, we believe, was too slow to accurately time and measure the temporal events that take place in the weld puddle. A system providing 600 to 900 pictures per second would be made more valuable. The normal video rate of 30 pictures per second may actually have been sufficient for completing the Phase I research.

An improved lighting system is a must if weld puddle surfaces are to be studied in detail.

The Extended Range Video (ERV) system probably saved months in the completion of these early feasability studies for **EDAP.** Most importantly some of the most significant details would have been missed. If not for video, it would have been highly improbable that the important discovery of the "Traveling Wave" would have been made. This was the result of ability to play back video tapes at a high speed. **It can therefore be concluded that video is an excellent tool for certain types of welding research.**

6.3 PULSE WELDING

The results of this research for pulsed GTA welding of A710 steels, confirms there are significant benefits to pulsed welding. When using either MILLI-PULSE or MICRO-PULSE methods, very predictable results can be expected. POLY-PULSE welding does not exhibit a straight line relationship to frequency.

6.3.1 PROCESS VARIABLES

1. Lower current levels can be used to obtain the same depth of penetration by either MILLI-PULSE or MICRO-PULSE welding as compared to steady D.C.

2. POLY-PULSE welding voltage readings are lower for the same arc length as MILLI-PULSE or MICRO-PULSE welding.

3. There was no noticeable accelerated electrode deterioration with any of the pulse combinations tested. As there is sometimes a MICRO-PULSE rate at which rapid deterioration occurs, the number of different pulse rates tested may have been insufficient.

4. Weld joints that have narrow gaps may actuall have reduced depths of penetration. (This may only be characteristic of welding A710 steels at the pulse rates tested.)

5. Removing the heavy scale on the plates is necessary as dirty, inconsistent bead shapes result. Any oxides may also interfere with the efficiency of the arc. As oxides are better electron emitters, energy is wasted in the oxides.

6.3.2 METALLURGY

1. <u>All</u> welds made by pulse welding showed refined grain structures.

2. All welds showed considerable dendrite fragmentation as compared to steady D.C. welds.

3. Breaking up of an Fe+Cu precipitate was observed in the pulse welds.

4. Even though the base metal had heavy porosity, there was no porosity in <u>any</u> of the pulsed welds.

5. The top surface of the pulsed welds showed considerable grain refinement.

There appeared to be very good mixing within the weld including at the interface. This more homogeneous structure should improve the welds in any HSLA steel.

6.3.3 NUGGET SHAPES, POLY-PULSE WELDING A710

A. POLY-PULSE welding produced three different weld nugget shapes, believed to be the results of convection flow patterns in the liquid weld pool.

The two commonly defined shapes are seen as <u>stable</u> puddle conditions.

1. INWARD FLOW (C/). Nuggets have deep penetration with narrcw top beads.

2. OUTWARD FLOW (C/). Nuggets have shallow penetration with wide top beads.

   A different bead shape was newly observed and is seen as an <u>unstable</u> puddle condition.

3. TRANSITION FLOW (C//). Nuggets exhibit some of the shapes of both the Inward (C/) and Outward (C/) flow convection patterns.

   Both the INWARD FLOW (C/) and OUTWARD FLOW (C/) bead shapes have very even bead geometries centered between the welding electrode and weld seam. The TRANSITION (C//) bead has irregular geometry and tends not to be centered on the weld seam.

B. These changing weld puddle and resultant nugget shapes, were observed at welding speeds of 1.5 to 4 I.P.M. A limited number of tests were made at 6 I.P.M. may not have shown these same characteristics. It might be that the TRANSITION (C//) type welds only occur at lower travel speeds and might also be related to bead size and/or current levels.

6.3.4 APPLICATION CONSIDERATIONS

A. For the highest quality welding of HSLA steels particularly in root passes, pulse welding shows definite advantages. Improved metallurgical properties should also better control and improve physical properties.

B. There are several types of welding power supplies that have outputs with preset frequencies. This includes standard 3 phase units, transistorized chopper types and inverter types. Some of these that have additional pulsing capabilities may have

resulting pulse combinations that could cause unstable TRANSITION (C//) types of welds.

C. This research work has demonstrated that two stable types of nugget shapes can be produced by different pulse combinations. The "Select-A-Shape" capability has potential in both multiple pass and single pass welding.

1. Single pass welds in thin sheets can employ the OUTWARD FLOW (C/) type welds.

2. Single pass weld in thick plates can employ the INWARD FLOW (C/) type welds.

3. Multiple pass welds might be accomplished as follows:

   a) Seal Pass - (if required) OUTWARD FLOW (C/) at a high speed
   b) Root Pass - INWARD FLOW (C/) for complete penetration
   c) Fill Passes - either shape as determined
   d) Cap Pass - OUTWARD FLOW (C/) may result in one wide smooth pass.

   In an automatic scenario bead shapes can be programmed for each pass.

The future application of higher strength HSLA steels and other alloys may require a process that can refine grain structures and maintain homogeneous alloying of the nugget. The pulse GTAW process continues to provide evidence that it may be the high quality process available for these purposes.

6.4 A710 STEEL PLATE

Developing a simp!e data base for pulse welding HSLA steels, using the specifi(analysis of A710 employed in this research, was not possible. ıny of the complexities of welding this steel are detailed throughout this work and should be of value to the welding engineer.

1. Full penetration welds in 3/8" thick plates, using square butt joints, resulted in welds too large.

   A. Grain growth may be unacceptable.

   B. Overheating is excessive.

2. Plates 1/4" thick can satisfactorily be welded with pulsed GTAW. However, prepared joints with 3/16" Lands might be preferred.

3. A magnetic arc control (MAPS) is necessary for prepositioning of the arc to avoid front wall interference. This allows welding at higher travel speeds, in thicker plates, at high currents.

4. Prepositioning the arc with a magnetic field increases the depth of penetration. When a strong magnetic field is employed for only stabilizing the arc, penetration is again increased. This is probably due to the focusing or constricting of the plasma.

Most of the process variables that are considered when welding mild steels can be applied to A710 steel. At currents up to 300 Amps for travel speed to 4 I.P.M., pulse GTA welding of A710 steel results in both quality improvements and metallurgical improvement. Caution should be employed when using the data developed for welding any other analysis of A710 or other HSLA steels.

6.5 GENERAL COMMENTS

Weld nugget size and particularly root bead width, has been successfully used by the welding engineer, as a means of predicting weld joint strength. This research confirms that the Natural Frequencies of the oscillating weld puddle has close correlation to nugget size. Unfortunately, the welding operator finds this frequency information is out of his range of observable parameters. Therefore, if automatic real time control of nugget size and penetration is to be accomplished, a precise method of sensing and control is needed.

EDAP research proves that frequency type observations can be made through the arc using "Recognition Software." Further, the very flexible **EDAP** "Intelligent Software" demonstrates the capability of providing the accurate data necessary for controlling the welding process in real time. Reliability of welding therefore can be greatly improved by automatic nugget size and penetration control employing an **EDAP** type system.

Pulse welding extends the GTAW process. Quality improvements and control have been proven by this research, employing several types of square wave pulse welding methods. Additionally, a **technique for determining weld bead shape has been discovered.** This adds a valuable tool to the welding engineer's selection of process controls. Ranges of observable bead shapes, selected by a wide variety of pulse rates, will result in predictable welding results.

The feasability of these individual capabilities has been clearly demonstrated. The possibility of successfully combining the **EDAP** system with pulse welding becomes obvious. The result is an advanced welding system offering major process controls. These will greatly improve both the reliability and predictability of welding for commercial and military applications, including welding HSLA steels.

7.0 RECOMMENDATIONS

The four areas of feasability research undertaken have all shown positive results, concluding in a high confidence level for these recommendations to continue research. Even though some of the future research can be accomplished both concurrently and simultaneously, the possibilities are detailed separately.

7.1 EDAP - ELECTRO DYNAMIC ARC AND PUDDLE CONTROL

The following research is outlined in preferred order of proceeding. Initial **EDAP** research should be limited to one base metal, probably mild steel.

7.1.1 INVERTED WAVE EXCITATION PULSE (P_e^-)

Limited initial testing showed promise that this diminishing current pulse technique may be the preferred method for puddle excitation. This should be confirmed by testing the following conditions:

A. Travel speed.
B. Gaps and joint design.
C. Penetration as related to thickness.

7.1.2 PID and DWCS (See Appendices F and G)

The hardware and software for this research control has been designed and manufactured. It can be used with either increased current excitation pulse (P_e^+) or, if proven more valuable, the diminishing excitation pulse (P_e^-). Welds will then be run, testing primarily for nugget size and penetration control.

7.1.3 MICRO-PULSE

MICRO-PULSING has shown to control both nugget size and shape along with smoothing the waveforms produced by the puddle. Modifications to the **EDAP** system will allow for the use of superimposed MICRO-PULSING. Testing under varying conditions should follow.

7.1.4 PROCESS CAPABILITIES

There will be some limitations to early **EDAP** implementation that need to be explored, such as:

A. Joint design.
B. Filler wire additions.
C. Multiple pass welding.
D. Various alloys.

7.1.5 WELDING POWER SUPPLIES

EDAP as originally conceived was to be an "add on" system to other welding equipment. As **EDAP** has been proven to work with a machine (Arcon POLY-PULSE) that normally produces a square wave, no further concept testing needs to be done. However, for general application, particularly for existing systems, further proving needs to be undertaken for the following:

1. Slower power supplies that will only produce a sine wave. This may require a square wave pulse generator attachment.

2. Slower square wave machines. These may also require a square wave pulse generator attachment.

3. Two torch welding. Faster welding, without significant widening of the bead, can be accomplished by such methods as tandem arc welding.

7.2 PULSE WELDING

A. Improved metallurgical properties have been documented for a variety of different metals. Some additional documentation should be undertaken for some of the new low alloy steels.

B. Both MICRO-PULSE and MILLI-PULSE have been shown to have a significant effect on increasing penetration. POLY-PULSE, however, has shown mixed effects on bead shape. All of the welds were made on A710 steel.

It is recommended that a series of welds be made on mild steel, stainless steel and a nickel base alloy to determine if the three bead shapes identified in this research will also be developed, particularly the newly discovered "TRANSITION" bead.

C. Another series of welds should be made to determine how effective both MILLI-PULSE and MICRO-PULSE is in controlling depth of penetration on the same mild steel, stainless steel and nickel base alloys.

D. The addition of filler alloys may possibly have an effect on puddle conditions when using pulsed welding. Therefore, all testing with the various alloys should include filler alloy additions.

E. Joint shape may also affect welds made by the pulse arc process. Again, various joint types including multiple pass welding should be researched.

7.3 DATA BASE

Much of the work required for continued **EDAP** and PULSE WELDING development will help provide a data base for the various alloys suggested.

It appears important to determine whether or not the specific analysis of A710 steel caused the encountered welding problems or whether all A710 steels will act the same.

7.4 EXTENDED RANGE VIDEO

Four major improvements to this system need to be considered.

1. Higher picture speeds, perhaps 600 or 900 pictures per second.

2. Improved lighting for the weld puddle.

3. Higher resolution recorder perhaps 600-1000 horizontal lines.

4. The addition of a Grid Line Generator for more accurate puddle measurements.

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10.0 GLOSSARY

(Special Terms used with this research work)

AVERAGE CURRENT - In pulse welding. Determined by adding the background current to the peak current dividing by 2, then adjusted for duty cycle.

BASE CURRENT - During a cycle of pulse welding, the current level that has a longer time (width) than the puddle. Can either be a higher or lower level than the maximum pulse according, to whether or not the pulse level is superimposed above the base current, or diminished from the base current.

CPS - Cycles Per Second. Used to describe the frequency rate of the oscillating weld puddle.

DARC - Data Acquisition, Reduction and Control. A computerized system which captures, stores, and processes arc voltage signals for **EDAP**.

DFT - Discrete Fourier Transform. A mathematical linear mapping of temporal data to a frequency domain representation.

DUTY CYCLE - During pulse welding, the time relationship of the amount of time welding current is at high or peak current to the amount of time weld current is at low current or at the BASE current level. Expressed as the percent of high current time to the total high plus low current time.

DWCS - Dynamic Weld Control Software. Designed to control weld puddle oscillation for the DARC system.

EDAP - Electro Dynamic Arc and Puddle Control. A system of induced pulsations of the welding puddle with real time feedback for controlling weld quality, puddle size and penetration.

EIR - External Interrupt Request. Signal external to the DARC which triggers an interrupt in computer execution that executes signal acquisition.

ERV - Extended Range Videography. High speed, high resolution system including various enhancement, measurement and control devices.

f_N - Natural Frequency. The sustained oscillations as related to the fundamental movements in an excited weld puddle, expressed in CPS or Hz.

FZC - Fusion Zone Characteristics.

AD-A168 762 RELIABLE WELDING OF HSLA STEELS BY SQUARE WAVE PULSING 2/2
USING AN ADVANCED..(U) APPLIED FUSION TECHNOLOGIES INC
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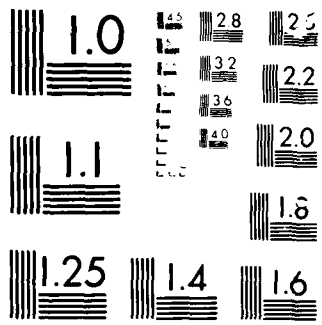
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HAZ	-	Heat Affected Zone.
HSLA	-	High Strength Low Alloy steels.
IP_e	-	Excitation pulse, current amplitude (Amps) (Positive or Negative going)
MAPS	-	Magnetic Arc Positioning and Stabilization. A device made up of a control plus electromagnet positioned at the welding arc.
MICRO-PULSE	-	D.C. Current Pulsing, 1K Hz to 50K Hz.
MILLI-PULSE	-	D.C. Current Pulsing, 1 Hz - 1K Hz.
OSCILLATIONS	-	The periodic up and down motion in a weld puddle about an axis parallel to the arc.
P_e^+	-	Excitation Pulse, Positive.
P_e^-	-	Excitation Pulse, Negative.
PID	-	Proportional Integral Differential. The control signal is based proportionally, integrally and differentially, on an error signal which indicates numerically how far the output is from a desired point.
POLY-ARC	-	Trade name for welding power supply manufactured by ARCON. Multiple arcs can be operated from a single power supply.
POLY-PULSE	-	Trade name for welding power supply manufactured by ARCON. Has the ability to both Milli and Micro pulse, plus superimpose one on the other.
PULSE AMPLITUDE	-	**(P_e)** The current excursion from Low or BASE current to pulse peak or High current. Example: 700 Amps High Current 300 Amps Background Current 100 Amps Pulse Amplitude (IP_e)
R_{Hz}	-	Resonant Frequency. The electrical signal produced (Hertz) as the result of the Natural Frequency, f_N, of the weld puddle.
SPI	-	Special Purpose Interface. Analog and digital circuitry specially designed to interface the welding machine and DARC.
V_a	-	Analog arc voltage.
V_W	-	Welding Velocity. The relative movement of the arc to the weldment.

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REPORT OF CHEMICAL/PHYSICAL TESTS

CERTIFICATE NO	DATE	PAGE
08232	NOV 19,1985	1

MILL ORDER NO	DATE
FM-49755 00	11/11/85

CUSTOMER ORDER NO: FU111105-C1

JOB/REQ NO.

SHIPPING NO	DATE
FM 08232	11/19/85

CARRIER: ABF

CAR/TRUCK NO: TRL

SOLD TO:
14338
APPLIED FUSION TECHNOLOGIES, INC.
P. O. BOX 9652
FORT COLLINS, CO 80525

SHIP TO:
APPLIED FUSION TECHNOLOGIES, INC.
1330 DUFF DRIVE
FORT COLLINS, CO 80526

THIS MATERIAL HAS BEEN MANUFACTURED AND TESTED IN ACCORDANCE WITH PURCHASE ORDER REQUIREMENTS AND SPECIFICATIONS

USM ALLOY STRUCTURAL PLATE
ASTM A710-84 GRADE A CLASS III
MODIFIED

PHYSICAL PROPERTIES

ITEM	DESCRIPTION	HEAT NO.	SLAB	YIELD PSI x 100	TENSILE PSI x 100	% ELONG 2 IN	% RA	HARDNESS BHN	BEND TEST	IMPACTS
1	3/8 X 48 X 96									
	HT 210106									
	5J1171A	210106		780	900	39				
	5J1171B									
	5J1171C									
	5J1171D									

CHEMICAL ANALYSIS

HEAT NO	C	Mn	P	S	Si	Cu	Ni	V	Cb	Al	Cr	Mo	Ti	B	McQuaid Ehn Grain Size
210106	.03	.40	.008	.012	.24	1.18	.80		.040		.70	.22			

I certify the above results to be correct as contained in the records of OREGON STEEL MILLS By K Lunquist Chief Chemist

FILLER WIRE TYPICAL CHEMISTRIES

	C	Mn	P	S	Si	Ni	Ti
W18 (Armco18)	.17	.91	.010	.008	.19	3.35	.15
W19 (Armco19)	.11	.71	.010	.010	.17	1.84	Res

	Yield	Ult. Tensile	Elong.
W18	77KSI	89KSI	27%
W19	80KSI	92KSI	25%

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DESCRIPTION ______ Contract ______

O'SCOPE ______ OTHER ______ OCV ______ TIME ______

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ANALYSIS ______

Name ______

APPLIED FUSION TECHNOLOGIES, INC., Ft. Collins, CO

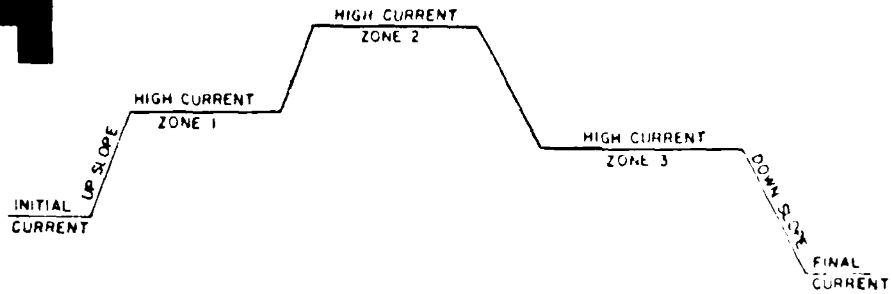
Appendix C

RESEARCH COMPUTER DESCRIPTION

The Hewlett Packard 9816 is a stand-alone computer based upon the Motorola 68000 microprocessor. As configured for this work, the 9816 has 512 kilo-bytes of internal random access memory (RAM) available for operating system, programs and data. Interfaces on the HP 9816 include one HPIB (IEEE-488) interface, one RS-232 Serial interface and one General Purpose Input/Output (GPIO) 16-bit parallel interface. Communication between the HP 9816 and the Special Purpose Interface is accomplished via the GPIO interface.

Automatic Welding Systems

ARCON ARC CONTROLS DIVISION - GUERDON



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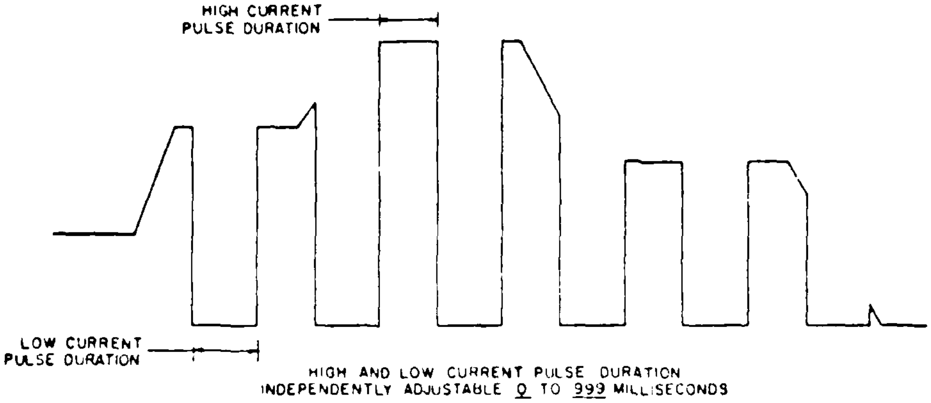

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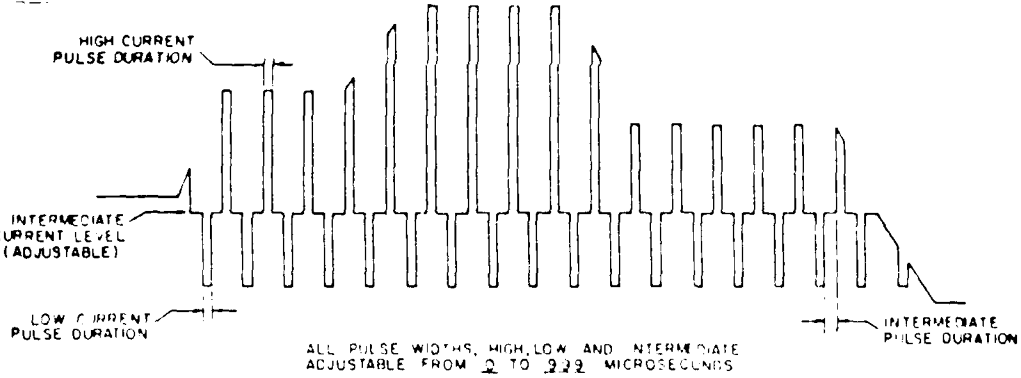
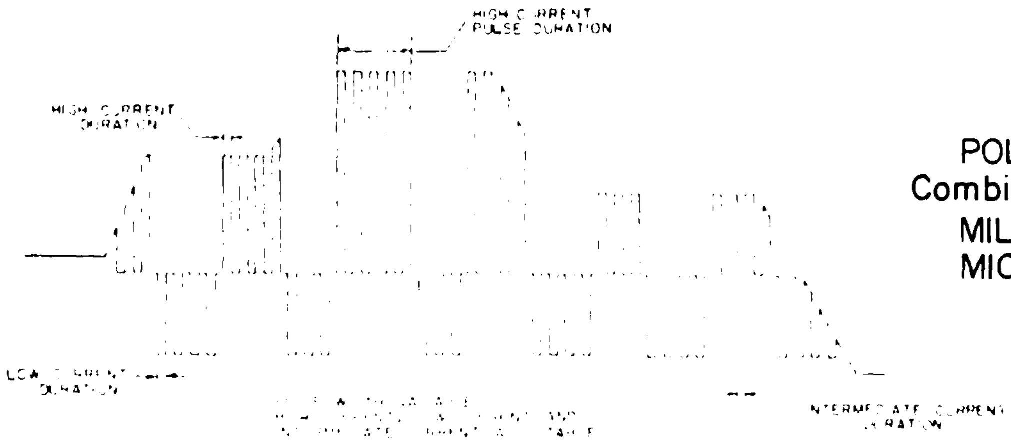


DC-MICROPULSE



POLY-PULSE Combination, MILLIPULSE Plus MICROPULSE

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FREQUENCY ESTIMATION ALGORITHMS

Several frequency estimation routines were used in the process of developing **EDAP**. These included a zero crossing detector, a peak detector, an unaveraged periodogram and an averaged periodogram. The zero crossing detector and the peak detector were both too susceptible to noise corruption and did not provide reliable frequency estimates. The averaged periodogram did not provide any significant improvement over the unaveraged technique and requires more time for computation. The unaveraged periodogram provides comparable results. Therefore the final frequency estimator employed was based on this technique.

The frequency estimator used in the **EDAP** development program is an approximate least squares approach. Given a set of M arc voltage measurements $\{V_a\}$ assumed to be derived from a system (i.e., an oscillating weld puddle) assumed to have the form

$$V_a(m) = V_{dc} + A\cos(wmT) + B\sin(wmT) + n(m) \qquad m = 0, 1, \ldots, M-1,$$

where w is the radian frequency of oscillation and T is the time interval at which the arc voltage is sampled and $\{n(m); m=0,1,2,\ldots,M-1\}$ is a sequence of random zero mean independent noise samples which may appear because of plasma oscillations in the arc or due to the effects of quantization of the arc signal. It can be shown (Ref. 19) that the approximate least square estimate for w is that value w which maximizes the function, $R^2(w,k)$, which is given as

$$R^2(w,k) = A^2(w) + B^2(w).$$

where $R^2(w,k)$ is referred to as periodogram. A(w,k) and B(w,k) are given as

$$A(w,k) = \sum_{m=0}^{M-1} (V_a - V_{dc})\cos(wmT)$$

and

$$B(w,k) = \sum_{m=0}^{M-1} (V_a - V_{dc})\sin(wmT)$$

where V_{dc} is calculated by averaging the M arc voltage data points. The estimate of the frequency of the puddle is related to the radian frequency by $f'_N(k) = w(k)/(2\pi)$ where the prime is included to indicate that this is not the final estimator selected for **EDAP** purposes. For each set of arc voltage data collected in the low time between the k^{th} and $k+1^{th}$ MILLI-PULSE a frequency estimate $f'_N(k)$ is obtained. In this manner the change in the puddle oscillation frequency can be tracked and an appropriate control signal calculated.

One can see the similarity between the equations for A(w,k) and B(w,k) to the real and imaginary components of the Discrete Fourier Transform (DFT). As such, some of the fast algorithm research that has been done on the DFT incorporated into the frequency estimation routine to enhance the operating speed of the estimation algorithm.

This frequency estimator was implemented and tested. Results showed that occasionally an estimate was obtained which was unlikely in terms of the rate at which a weld puddle could change size. This caused scatter in the puddle oscillation frequency versus time data and would have resulted in a physically unreasonable control strategy.

A modified frequency estimator was then constructed which is a weighted average of the previous two estimates and the most recent estimate. That is the averaged estimate is given by

$$f_{N(k)} = \alpha_0 f_N(k) + \alpha_1 f_N(k-1) + \alpha_2 f_N(k-2)$$

The weighting coefficients are dynamic and are defined as

$$\alpha_0 = \frac{1}{2}\frac{(v_1 + v_2)}{v_t}$$

$$\alpha_1 = \frac{1}{2}\frac{(v_0 + v_2)}{v_t}$$

$$\alpha_2 = \frac{1}{2}\frac{(v_0 + v_1)}{v_t}$$

and

$$v_{k-i} = \sum_{m=0}^{K} (R(w_m, k-i) - R_{k-i})^2$$

and

$$v_t = v_0 + v_1 + v_2$$

where $R(w_m,k)$ is the discrete version of the k^{th} periodogram and R_{k-1} is the average energy in the periodogram.

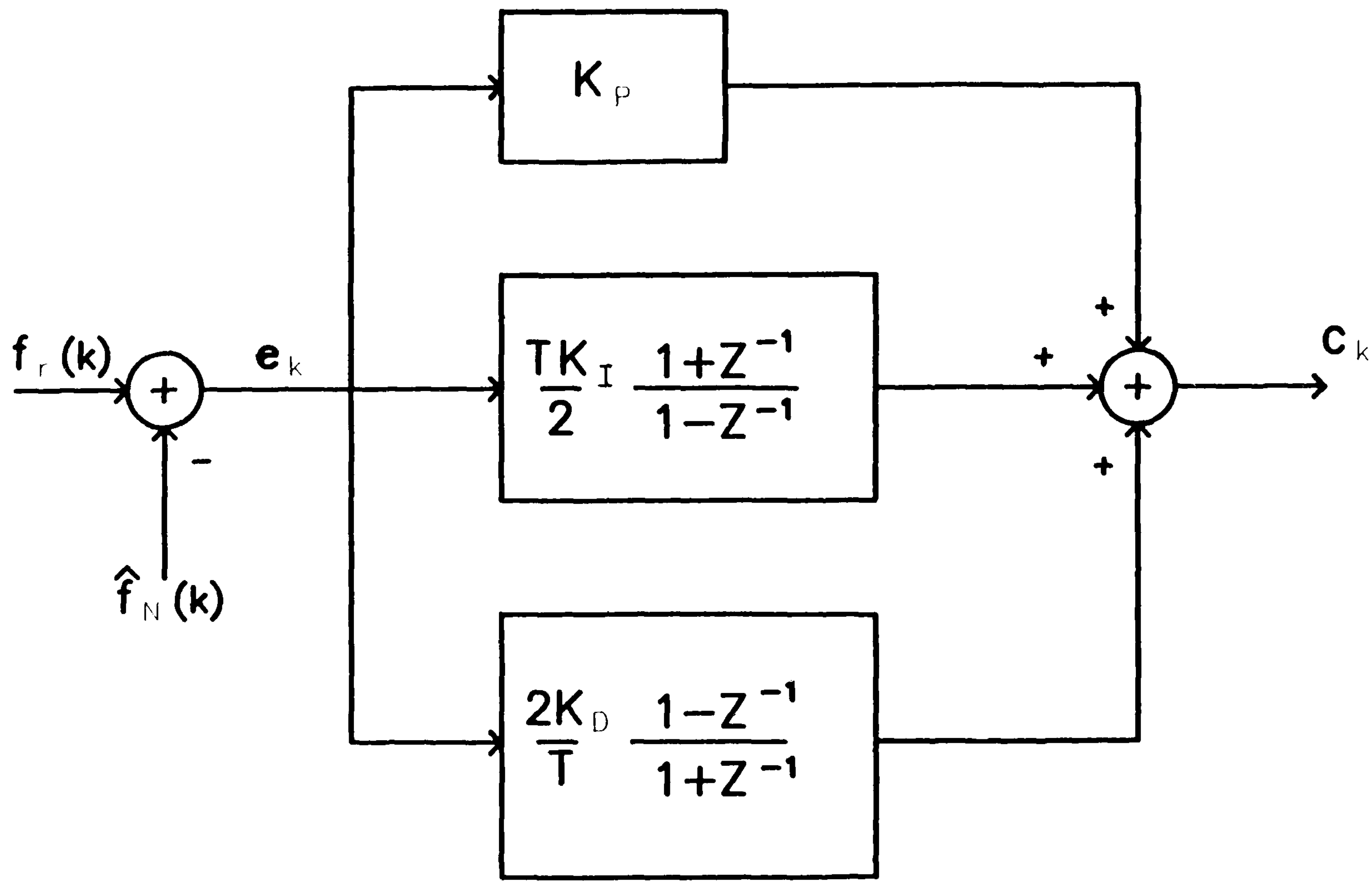
This final estimator implemented, weights the frequency estimate according to how spread out the arc voltage energy is in frequency. That is, if the energy for the k^{th} record of arc voltage is tightly spread around the frequency that maximizes R(w,k) then that estimate should be weighted heavier than one whose energy is spread over a large frequency range. This frequency estimator gave more stable results and simplified the design of EDAP welding control system.

PROPORTIONAL INTEGRAL DIFFERENTIAL CONTROLLER (See Fig.19)

The controller was designed in continuous time and then converted to a discrete time implementation via a bilinear z-transform. The difference equation resulting from this approximation is given by

$$c_k - c_{k-2} = e_k\left(K_p + \frac{T}{2}K_I + \frac{2}{T}K_D\right) + e_{k-1}\left(K_p + \frac{T}{2}K_I - \frac{4}{T}K_D\right) + e_{k-2}\left(\frac{2}{T}K_D\right)$$

where K_p, K_I, and K_D are the gains of the proportional, integral, and differential segments of the controller respectively.



FUTEC
28 April 86

Figure 19

PID controller
for EDAP System

PROPOSED EDAP CONTROL
DYNAMIC WELDER CONTROL SOFTWARE (DWCS)

The **DWCS** will perform the following steps: (refer also to Figure 20 and Section 2.3.4D, Page 51)

Step 1 - The computer will select external control of the welder current levels, both BASE and excitation pulse (P_e). This is done under software control of the computer rather than a hardware switch to assure that the computer is ready to assume control of the welder before actual control is transferred. The welder currents will initially be set to zero.

Step 2 - Once the computer has successfully assumed control of the welder, the operator is prompted to assure that the non-computer controlled weld parameters such as millipulse frequency, duty cycle, gas flow rates, etc. have been properly set. Those parameters which have direct impact on the weld will be entered into the computer for later reference.

Step 3 - When all the preconditions have been specified and satisfied, the computer will increase the weld currents to a predetermined startup level, this level being small compared to the expected nugget size and penetration current level. The operator will then be prompted to strike the arc. High frequency arc starting under computer control, while possible, was not implemented in Phase I in an attempt to reduce the number of external influences for **EDAP**. After the arc start period, the computer will monitor the D.C. arc voltage and consequently will be able to recognize the instant when the arc has started. Some few seconds delay will be allowed to assure a stable arc has indeed been established at the low static startup current.

Step 4 - If travel is not programmed for automatic sequencing, the computer will prompt the operator to start weld travel, then signify to the computer that travel has indeed started.

Up to this point in the weld, computer control of the welder has been limited to static setting of the weld current at a low startup value. Dynamic feedback control of the weld pool has been initiated at this point. Step 5 initiates that dynamic control.

Step 5 - The computer will initiate frequency estimation for determination of weld pool size and penetration. The estimates will cause the computer to increase BASE current and change the excitation pulse (P_e) current levels until a stable penetrating weld is established. This is as recognized by a stable weld pool oscillation

in a predetermined frequency range. The **DWCS** software will then maintain this stable freqency for the predetermined frequency, via a proportional integrating feedback control algorithm.

Step 6 - The weld pool and nugget size established in Step 5 will be maintained until the operator signifies to the computer, unless under automatic control, that the end of the weld has been reached. The computer will then terminate dynamic control and decrease the weld currents in a predefined manner to arc termination.

Step 7 - The resulting weld can now be compared for size, penetration and quality to the waveforms of the weld pool oscillations as recorded by Extended Range Videography (ERV) and frequency estimates by computer printouts. Modifications or improvements to the control scheme can be implemented if required, for additional welding control research.

The welding scenario has been computer simulated using a simple model for the puddle oscillation frequency. (Complete implementation of the **DWCS** has not been achieved due to time constraints.)

PROPOSED EDAP SYSTEM

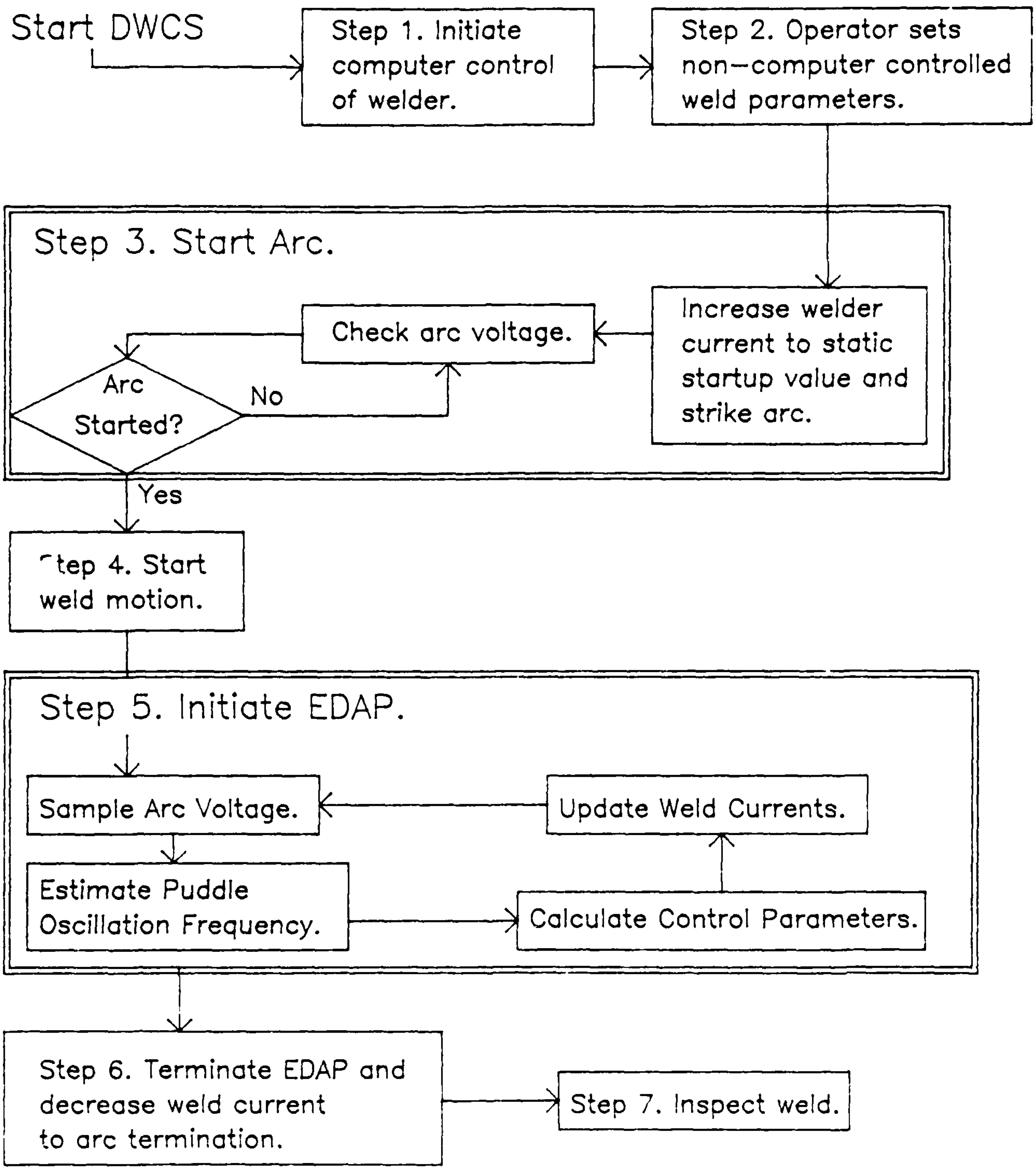


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Figure 20

END

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